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Subadult Cortical Bone Analysis As An Indicator of Childhood Health Status Among the Tipu Maya Population

Jaime Thomas

SUBADULT CORTICAL BONE ANALYSIS AS AN INDICATOR OF CHILDHOOD HEALTH STATUS AMONG THE TIPU MAYA POPULATION

by

Jaime Elizabeth Thomas

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Approved by:

Dr. Marie Danforth, Committee Chair
Dr. Bridget Hayden
Dr. H. Edwin Jackson

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ABSTRACT

This thesis explores juvenile health at the contact Maya site of Tipu in western Belize. The associated cemetery was excavated and provided a large and well-preserved population. Although Tipu has been a focus of many studies, few studies have focused on subadults and none on their cortical development, which can allow insight into access to necessary nutritional resources.

Some 108 femora belonging to individuals aged birth to 13 years with femora previously sectioned at midshaft provided the sample. External dimensions taken included diaphyseal length, circumference, medial-lateral diameter and anterior-posterior diameter. Additionally, cortical thickness was measured at four points, and 95 femora were analyzed for cortical area using the software BoneJ. It was expected that overall the reduced cortical bone maintenance would be seen as the result of the protein-deficient maize diet and differences by burial location might be present.

The results of this study exhibited a generally healthy population of juveniles. The diaphyseal measurements and cortical area articulated steady growth throughout childhood with greatest velocity during infancy and adolescence. No differences by burial location are seen, however. Evidence of premature osteoporosis, as observed among the ancient Nubias, was not present. Overall, these results generally align with other bioarcheological inquiries done on the health maintenance of the subadult health status at Tipu. This study sheds light on a Tipu child’s experience of a Maya society during the time of the Spanish’s arrival and also provides a baseline of cortical bone data that might be used in future studies from the region.

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DEDICATION

I would like to dedicate my thesis to my amazing, supportive parents, Laura and Ellis Thomas, for your confidence in me in my academic pursuits. I am indescribably grateful for the many opportunities you have given me, and without your love and support, I would not have gotten to where I am today. Also, to Winston, the best fur baby a girl could have.

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CHAPTER I - INTRODUCTION

When analyzing skeletal remains as a means of understanding a past population, it is important to recognize the strengths and limitations bioarchaeological data can provide. The amount of bone gain and growth in early childhood development is a significant factor in reflecting general health. Appropriate nutrition in early life stages is critical to proper bone growth. Nutrition can have significant long-term effects too, such as how inadequate early bone development can be a main element of adult osteoporosis (Manifold 2014). Overall, low bone mass in subadults is indicative of specific factors that influence bone development pertaining to childhood diet, physical activity, and anthropometric characteristics, making its observation a powerful comprehensive health indicator. This is especially true in bioarchaeological studies since cortical bone is an ideal resource for data, especially when found well-preserved, due to the enduring inorganic material that it provides as compared to cancellous bone.

Juveniles, specifically in ancient populations, are significant to understanding the variability of afflictions that one could experience during childhood. In fact, it has been anecdotally argued that their health is a good barometer of the health of the entire group; thus, the study of cortical bone patterns in children is a powerful comprehensive health indicator (Bogin 1994:22). Among the settings in which health likely was impacted the most during the last several centuries is the New World with European contact. The Maya site of Tipu, which is found on the banks of the Macal River of western Belize, is an exceptional site with which to study changes brought about by the Spanish due to the excavations in the early and mid-1980s that led to the discovery and recovery of over 500 individuals buried around and in a Spanish style *visita* mission church (Cohen et al.

1994). Although located on the fringes of the Spanish frontier, the health of the population of Tipu still would have been affected by specific factors such as diseases and economic changes that were introduced through the contact period. It even served as a center for indigenous refugees fleeing from Spanish presence elsewhere in Yucatan and surrounding regions (Graham, 2011).

The human remains recovered from the site have since been extensively analyzed to better understand the general health and demographics of the Tipu Maya population before and after the time of contact (Cohen et al. 1994, 1997). Overall, the adults appear to have fared well according to pathological and metric observations of their remains, although the population is demographically unique with its high proportion of young adults. However, the children of Tipu have, for the most part, been overlooked as a source of pertinent information to a better understanding of the health status of the site's inhabitants.

This thesis examined the general health of the population at Tipu by measuring and analyzing cortical bone area in the femoral midshaft of juveniles from ages two to twelve. Based on findings from the few previous studies of children at Tipu (Armstrong 1989; Bianchi 2020; Gomberg 2018; Harvey 2011, Herndon 1994, Wrobel, Danforth, & Armstrong 2002), it was anticipated my analysis would reflect a population of juveniles that appeared relatively healthy, but further observations would help to reveal potential causes of their early deaths. Most notably, it was thought the juveniles of Tipu would exhibit nutritional deficiencies, including possible protein deficiency, due maize being the primary dietary staple (Garn et al. 1969; Graham et al. 1989:125). Thus, the cortical bone among the juveniles would most likely increase in diameter, but not thickness, with age since the latter only increases due to proper nutritional supplement. In addition, I expected that juveniles in the youngest age groups would show the most signs of bone increase whereas juveniles in older age groups would reflect the decrease velocity of bone growth.

Specifically, three hypotheses were tested in this study:

- That Tipu would have longitudinal and transverse bone dimensions that would increase with age in patterns comparable to those seen in other populations, although Tipu would be shorter.
  - That differences in these metrics would vary according to burial location
- That Tipu would not display premature osteoporosis as indicated by longitudinal growth at the expense of cortical growth
- That Tipu would have total cortical areas that would increase with age in a pattern comparable to those seen in other populations

In general, the bioarchaeological data present from Tipu, specifically the juveniles of the population, provided insight into the health of various age groups during childhood, and indeed potentially into the health patterns of the entire population. Analyzing the cortical bone of juveniles helps to articulate and highlight the struggles or benefits of being a child on the precipice of a civilization introduced to Spanish contact.

CHAPTER II - HISTORY OF THE TIPU MAYA AND THE ROLE OF CHILDREN

This section reviews the ethnographic literature and corresponding bioarchaeological data about the lifeways represented at the site of the Tipu Maya in Belize, specifically those of juveniles. The work discusses the evidence relevant to the Tipu area to understand the social and economic reorganization the residents underwent with the arrival of the Spanish and to understand those contact period variables especially significant to the growth and development of children.

Spanish Missionization and the History of Tipu

The site of Tipu shows evidence of occupation dating back to the Classic period, A.D. 250, and withstanding at least 175 years of European contact until AD 1707, when the site was forcibly abandoned by the Spanish (Cohen et al. 1994; Graham 2011). Tipu is located on what archaeologists have coined the fringe of the colonial frontier situated near the banks of the Macal River in west-central Belize (Figure 1) At its height, Tipu was a wealthy economic and politically influential center. The European missionization strategy, specifically that of the Spanish, recognized these facets of economic prosperity and political influence among the Postclassic Maya, essentially using these preestablished political centers to their advantage to gain momentum in their mission movement and to attain political dominance (Graham 2011).

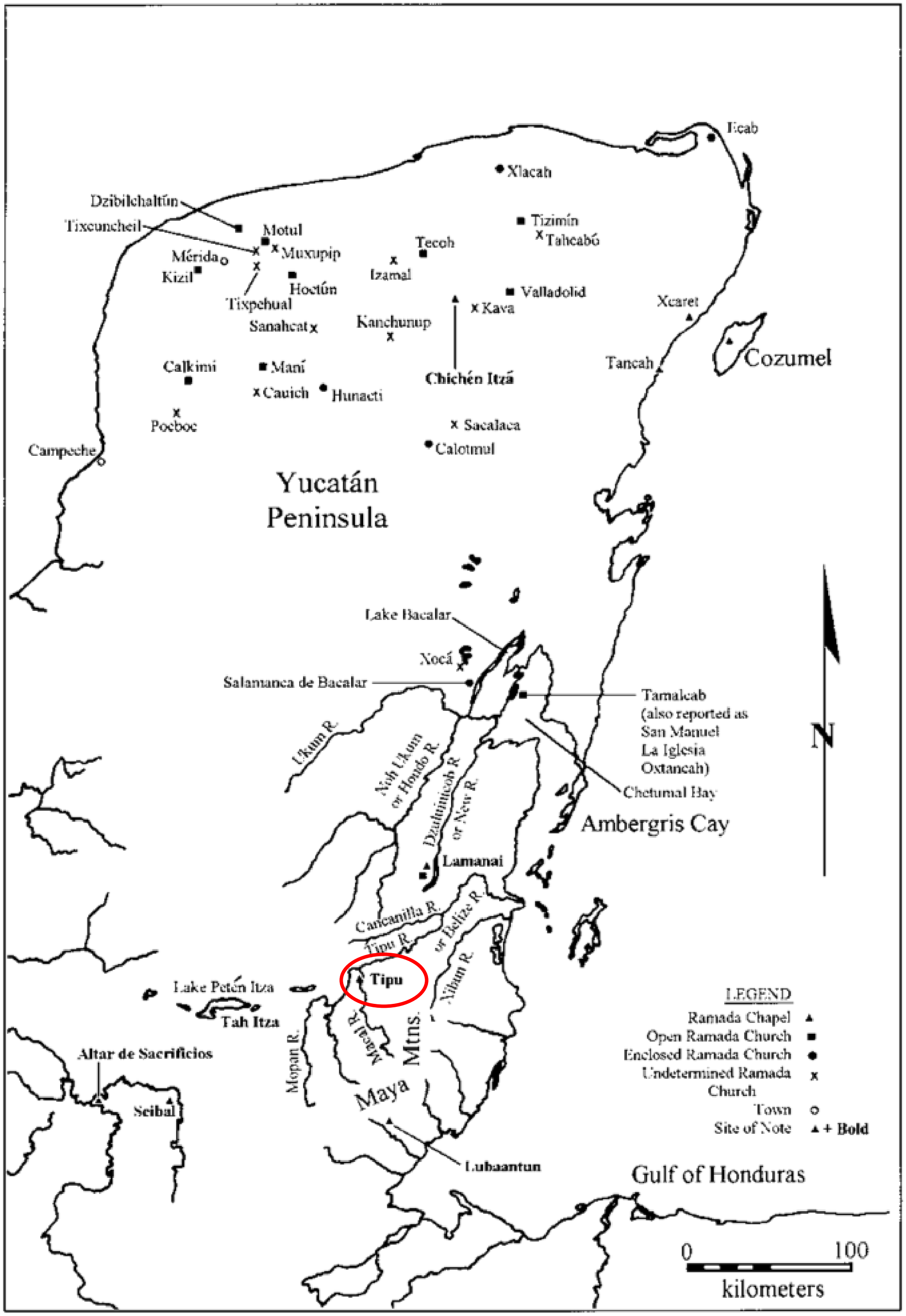

Figure 1. Location of Chapels and Churches of the Yucatán Including Tipu, Belize (circled in red) (Jacobi 2000:7).

However, considering its location, the Tipu community became an intermediary between the Spanish infiltrating from the north and east and the remaining uncontacted Maya sites to the south and southwest (Pendergast, Jones, and Graham 1993). The Spanish maintained their political dominance through establishing *encomiendas*, or land grants, to Spanish individuals that involved forced labor and tribute from the indigenous population. Corresponding to the establishment of the *encomienda* at Tipu in 1544, a *visita* mission church was also constructed to help impose Christian beliefs.

Exploring the characteristics of life at the site of Tipu provides context as to how the Tipu Maya reacted to the Spanish contact and how the native population's lives and lifestyles were affected. Simmons (1995) argues the archaeological evidence suggests consistent trade between Tipu and the Itzá Maya in the Petén region to the west, which is significant to understanding the power relations manifesting at the time of Spanish arrival. Ultimately, Tipu's isolation helped to protect the Maya community from the Spanish goal of dismantling the preestablished indigenous economic systems and cultural beliefs. Graham (1989, 2011) notes that objectively the Spanish had little impact on the Maya material culture and subsistence patterns.

However, archaeological evidence exposes evidence of both acceptance and rejection of the Spanish's influence from the Tipu population. The burial practices observed at Tipu emphasize at least nominal participation with Catholicism and in the missionary efforts, considering the number of individuals who were buried in and around the church (Cohen et al. 1994; Jacobi 2000:99). Jacobi (2000:109) writes,

The Tipuans were sufficiently involved in Catholicism to hold some type of special position within the church as indicated by the female whose grave in the nave held a religious censer; it seems unlikely that a Native American woman would have actually held a position within the church when only in the late twentieth century have European and United States Catholic women been grudgingly permitted any official positions other than as nuns.

Additionally, ethnohistoric accounts acknowledge Tipu's principal leaders, Cristóbal Ná and Francisco Cumúx, as active participants in the church and faithful leaders, recognizing that Ná gave his life for a friar in efforts to convert the Itzá (Jacobi 2000:20). Another example of the testament of the Tipuan Catholicism occurred in A.D. 1623 when 80 Maya males traveling with the friars on a conversion mission were killed by the Itzá (Jacobi 2000:189).

In contrast, some of the archeological evidence uncovered at the site may represent a population that was mostly complicit with the Spanish missionary efforts, but the spirit and long-standing Maya religious beliefs were still evident. At Tipu, an idol of a pre-Columbian God was found buried among the construction process of a building, and the ultimate abandonment and desecration of the church at Tipu reinforce the archaeological evidence of a Maya group not entirely accepting the Spanish culture (Jacobi 2000:195). Most likely, after the extensive loss of Tipu men on that conversion mission with the friars, the Tipu community was devasted and possibly channeled a religious intolerance and discontent that resulted in the desecration of the Tipu church around A.D. 1638 (Jacobi 2000:189). This desecration could have contributed to what the Spanish would consider an act of violence against the Catholic religion. Thus the interaction between Maya and Spanish at the site was complex and changed over time.

Children at Tipu

The lives of children at Tipu during this crucial time have received less attention from Maya bioarchaeological inquiries. The burial locations of juveniles may be a significant indication for the status or role of children within the Tipu since most were interred at the back (away from the altar) of the church nave, possibly reflecting the idea those who were buried closer to the altar were considered closer to God and thus of higher status (Jacobi 2001:59). This implies that children were not held in the same regard as the adults of the society. However, in general, the daily life of a Tipu child would include involvement with work at the church and furthering their training in Catholicism with the practice of catechisms (Jones 1989:216) in addition to their other more mundane daily activities. Ethnohistoric reports detail the participation of children in the Spanish missionary efforts, especially their conversion to Catholicism.

Evidence of traditional Maya subsistence on maize, squash, birds, and fish indicates they were available to all the population of Tipu, including the children (Cohen 1994:129). Very young children, specifically infants, relied on breastmilk as the most significant source of nutritional growth. After a certain age, when the child was weaned, their source of nutrition can greatly affect current and future health. Hiers observes, "Ethnohistoric records from Diego de Landa, a friar brought to the Yucatán in AD 1549, indicate that, before Spanish contact, Maya children were weaned between three and four years of age" (2014:75), and her investigation of the age of weaning at Tipu using isotope analysis essential confirmed this. Records also indicate that the demands on women of Tipu, such as domestic labor and child-rearing, significantly increased after Spanish conquest (Clendinnen, 1982), a fact that might have impacted the age at which infants were weaned (Hiers 2014; Landa 1941:125; Williams et al. 2005). Considering Tipu children were mostly weaned by the age of 3, the diet of older toddlers, children, and adolescents would likely have been versions of the standard Tipu diet.

Children also were a significant aspect of social and economic culture. Among the Tipu Maya children, sex-role socialization especially had an impact. The Maya was dominated by the patrilineal society divided by gender lines, where women were associated with activities around the home and men more with those related to subsistence (Storey 1992). Of the economic activity of children at the site, Herndon (1994:30) writes, “Among the Maya, women (and girls) assume production roles involving the household, whereas men (and boys) take on roles that pertain to agriculture…examination of sex-role socialization among children investigates differences along socially created gender lines within society, but also views socialization into the workforce.” Girls were expected to participate in domestic activities such as doing laundry, sewing, or mending clothes, and assisting their mothers. In contrast, boys were seen as opportunities of labor, especially at an earlier age, due to their sociocultural activities such as harvesting a field, cutting the forest for milpa, or helping run a store.

Thus, the sociocultural variation among the children of Tipu was directly associated with the economic opportunity that came with their economic potential; boys were seen as more of an economic asset, which came at an earlier age than for girls due to the money associated with the work available. The economic contribution of Tipu women and girls were tasked with weaving *mantas,* a tribute item to the Spanish, and their embroidery skills were significant to the established trade systems of cotton textiles of the Maya (Herndon 1994:231). In general, little information exists on the daily domestic lifestyles of children, but specifically subadult females.

The Cemetery at Tipu

The cemetery at Tipu was excavated in the 1980s by Mark Cohen and colleagues (Cohen et al. 1994), discovering the remains of over 550 individuals. Tipu culturally maintained the Christian burial method as indicated by the style of burials with most being single primary interments encased in shrouds with individuals lying on their backs with hands crossed over the chest or pelvis. Cohen et al. (1994:80) note, “Burial furnishings consist only of the shroud pins or relatively simple jewelry which were most often found with children.” The lack of grave goods emphasizes Tipu’s conformity to Christian burials, but in general, there are no clear trends seen concerning them with juvenile burials.

In terms of location, juvenile burials were abundant both inside and outside the church but did show a noteworthy difference in terms of the distribution. They accounted for 33.08% of burials within the church as compared to 50.4% outside of the church, a difference which is statistically significant (Jacobi 2000:106); this likely reflects their lower status compared to adults. Only 10% of burials found inside near the altar of the church are children, and no burials of children under two years old were found near the altar of the church, most likely due to their ineligibility from being unbaptized (Jacobi

2000:107); priests were not resident at the site, and at times several years might pass between their visits to Tipu.

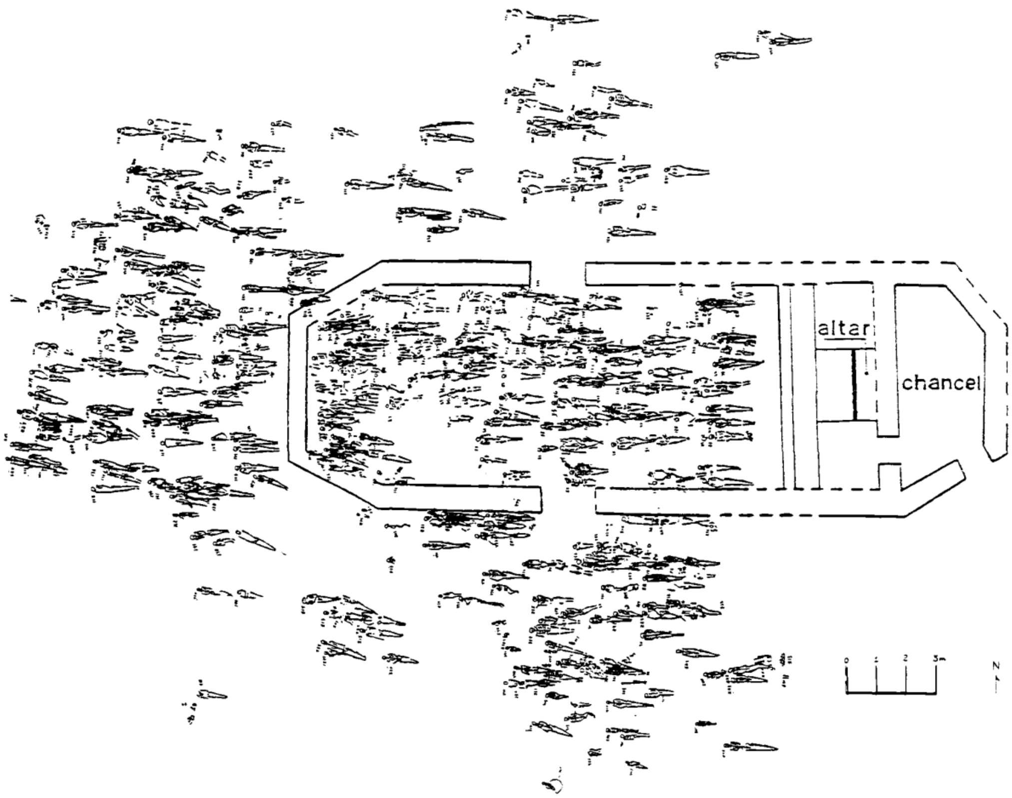

Figure 2. Map of Church and Burials at Tipu (Jacobi 2000:15).

The lack of evidence of stacked or overcrowded burials in the nave of the church emphasizes a component of high-status individuals and active participants of the church to be allowed buried very close to the consecrated altar area. The back of the nave in contrast exceeded capacity, which could indicate an influx of Tipuans pursuing a burial within the church. Jacobi (2000:107) explains, “At the back of the church, disturbance of original burial interment areas or reuse of burial space was common, especially near the back wall of the nave.” The burials at the front of the nave were undisturbed, as well as closer to the altar, thus emphasizing the potential of more high-status individuals.

The burials excavated at Tipu are a significant indicator of the influence of Spanish contact, but the skeletal series does not represent an admixture of two different ancestry groups; rather, it appears to be entirely Maya based on dental traits (Jacobi 2000). The demographics of the Tipu burial data indicate 173 males, 119 females, 47 adults of unknown sex, and 249 children. Age-at-death estimates found the population ranged from age 0 to 45 (Cohen et al. 1994). Most adults, however, died young, before age 30, which conceivably may have been related to the epidemics that devastated those directly in contact with Europeans, but no sign of mass burials was discovered. Tipu's remote location allowed for inconspicuous relocation of individuals from Maya populations infiltrated by the Spanish, thus creating a refugee center for displaced individuals from surrounding sites disturbed by the Spanish. This most likely contributed to the predominance of a younger population in Tupu, specifically subadult males (Jacobi 2000:180).

Juvenile Health Patterns at Tipu

Overall, the Tipu population appears to have been relatively healthy according to observation of their remains. Cortical bone analysis in adults suggests there was reliance on maize prepared with limestone and ash since bone maintenance indicates good calcium and phosphorous ratios (Cohen et al. 1994). Cohen et al. (1994) found that systemic infection in the adult population afflicted only 9.9% of males and 7.5% of females. Frequency of anemia was observed through the presence of porotic hyperostosis and cribra orbitalia, and data showed that of 214 individuals with at least one or two intact orbits, cribra orbitalia occured in 8.8% of men, 5.4% in women; the results indicated lower frequencies than what is generally seen in other Maya sites (Cohen et al.

1994). Frequencies of porotic hyperostosis were quite similar. Therefore, widespread chronic illness was not an issue for the Tipu Maya from the perspective of the excavated skeletal series. The Tipu population also displayed typical adult Maya stature; Cohen and colleagues (1994:129) note, “They do not appear to indicate growth was compromised by significant economic deprivation relative to precontact populations.” However, the osteological paradox (Wood et al. 1992) could also be at play where a rapid death from disease resulted in no effect on the bone.

Although they are a mortuary sample, the children at the site also were generally healthy. Among limited studies of the juveniles at the site, Cohen et al. (1994) found that 30.5% of children showed signs of anemia; in comparison, in the Postclassic period of Chichen Itzá in northern Yucatán showed evidence of 77.5% frequency of anemia among subadults (Wright and Chew 1999:925). Wright and Chew (1999:925) stated, “We observe that porotic hyperostosis is generally less common in late Prehispanic and early Colonial skeletal series (Tipu, Lamanai, Iximche) than during the Classic Period at inland sites where maize consumption was high (the Pasion, Copan).”

Looking at another health indicator, Harvey (2011:72) observed the frequency of linear enamel hypoplasia among juveniles. She found that out of the 77 subadult central incisors scored, 84.4% proved to be affected by hypoplasia. Though a large portion of juveniles exhibits defects of the central incisor, most episodes were very slight. Harvey compared Tipu’s data to the hypoplasia data of the site of Lamanai, noting that Tipu’s population, although exhibiting a higher frequency of health defects, had episodes that were significantly milder in nature in comparison to those at Lamanai who experienced greater chronic stress (Harvey 2011:84). In addition, only 1.1% of Tipu juveniles showed evidence of infection (Armstrong 1989), a rate also observed by Bianchi (2020). Although infection was rare, there was most likely a reduction of population density during the time of contact, which may be one reason why Tipu did not appear to experience any epidemic disease.

Additionally, Gomberg (2018) analyzed the subadult burials found at Tipu for scurvy, specifically looking at the temporal bones, greater wings of the sphenoid, and dentition. In general, she found that subadults between the age of six to fifteen sustained the highest rate of lesions out of the population, with 33% affected (Gomberg 2018:8). However, her results emphasized a population that experienced scurvy at a lower frequency and milder severity of the cases seen in other Maya populations. Despite the abundance of vitamin C a tropical climate can provide, Gomberg acknowledged food processing and food preferences as main contributors to the evidence of scurvy in the Tipu population.

In general, the Tipu Maya lived relatively healthy lives, despite the early age of death for many, and the juveniles appear to have been in relatively good health as well, although it must remember that they did succumb to something at a young age. Overall, the skeletal analyses reflect a population successfully negotiating contact with Spanish missionization efforts, some of which might be attributed to the tumultuous effort it took to get to Tipu. However, one aspect of their health that has not been extensively studied but could potentially provide further information is their cortical bone development status.

CHAPTER III - ANALYSIS OF CORTICAL BONE

The health of juveniles in a population is a barometer of the general success of what the greater population would be experiencing. Children are especially vulnerable to various health disruptions during their growth; the younger they are, the more compromised their health might be by certain environmental or social afflictions (Huss-Ashmore 1982:25). Therefore, juvenile health indicators at Tipu allow for insight into disease and nutrition at the time of contact and/or shortly before the time of contact with Spanish. Additionally, among the indicators for children that may be studied, cortical bone maintenance is of particular interest due to how it reflects nutritional deficiencies.

The skeleton goes through major developmental changes throughout childhood and adolescence, in both size and shape, which result in an increase in length and mass. Juvenile bone is less dense and more porous compared to that of adults in both types of skeletal tissue, cortical and trabecular bone. The cortical bone forms the dense outer layer of all bones and the thick, dense walls of long bones. Cortical bone is essential to the skeleton due to the protective layer it forms around the internal cavity, and it provides body structure and weight-bearing ability (Manifold 2014; Mays et al. 2009:411). Trabecular bone, which resembles a honeycomb network, is located at the epiphyseal ends and the medullary cavities of long bones and within the axial skeleton (Manifold 2014). Within the trabeculae is bone marrow which contributes to the production of red blood cells and helps store fat (Huss-Ashmore 1982:52). The skeleton consists of about 85% cortical bone, whereas trabecular bones make up about 15% (Manifold 2014:5).

Accounting for 80% of the skeletal mass, cortical bone development and maintenance is correlated to the health of the individual; the greater the amount of cortical bone, the more likely the individual has maintained sufficient nutrients throughout their life, or at least through adolescence. Cortical bone is significant due to its role as a hard-outer shell and defining shape that acts as a strong site for entheseal attachment. Major variables influencing cortical bone maintenance are bone modeling, remodeling, response to mechanical forces, and malnutrition (Huss-Ashmore 1982).

Bone modeling is the process of bone sculpting in childhood and adolescence which can become a major variable with the growth and development of cortical bone. Childhood and adolescence are times of critical growth for the skeleton when proper nutrients are warranted for proper growth and function. A healthy juvenile has cortical bone that is constantly being remodeled, with up to 50% cortical remodeling each year. Huss-Ashmore (1982) observed how nutritional interference could affect the integrity of the potential of growth for an individual. In the case of bone modeling, she emphasizes the necessity of a high-energy diet and proper vitamins. In order for proper biological function and development, adequate nutrition is fundamental (Huss-Ashmore 1982; Mays et al. 2009:415). Bone is composed of crystalline salts, calcium, phosphate, citrate, and carbonate, and these components are reliant on sufficient protein and vitamins (Huss-Ashmore 1982).

Nutritional deficiencies are a major variable in influencing the growth of cortical bone. If an individual lacks critical vitamins or protein, it will restrain the development of proper growth. One deficiency primarily affecting bones and seen among juveniles most significantly during the Industrial Age is vitamin D (Huss-Ashmore 1982). Insufficient vitamin D in childhood and adolescence, known as rickets, can completely alter an individual's stature and general bone structure. Rickets causes bowing and twisting of long bones, generally the femur and tibia, in response to a lack of vitamin D, which in turn affects the integrity of the cortical bone growth and maintenance, and overall, the individual's stature (Hummert 1983:168).

Huss-Ashmore (1982) conducted a study of juveniles from post-medieval Europe in which a large number of adolescents showed signs of rickets, and which was correlated to the transition of urbanization in society. Wells (1975:755) studied burials from a historic site in Norwich, England, dating to the Industrial Age that further articulates the correlation of rickets and a more urbanized society. The long bones, specifically the femur and tibia, exhibited severe effects of rickets and an increase in the appearance of rickets in general, with the onset of the economic practices of the industrial age (Huss-Ashmore 1982:409).

Vitamin C deficiency, commonly associated with scurvy, is another variable known to affect the growth and development of bone. Indications of vitamin C deficiency can be seen with bowing and thinning of the long bones. Gomberg (2018) specifically employed the greater wings of the sphenoid and temporal bones for an analysis of the presence of scurvy in the Tipu Maya population. However, Agarwal (2016) notes the challenge in recognizing specific vitamin deficiencies due to the variability in their manifestation. Both vitamin C and D are difficult to distinguish in archaeological bone considering how poor preservation could affect the appearance of an actual vitamin deficiency, and similar skeletal symptoms characterize many deficiency syndromes.

Vitamin A deficiency is not as commonly seen in archaeological populations but still can affect the development of cortical bone. The human body already maintains a steady access to the vitamin A constantly being synthesized in the liver; however, in certain human populations, vitamin A deficiency can be attributed to a lack of variety in the diet (Huss-Ashmore 1982). Vitamin A deficiency can generally be seen as the bone gets thicker rather than longer since the osteoblastic activity focuses on the non-marrow surface compared to osteoclasts present at the marrow cavity. The increase in the volume of the bone is generally seen in long bones and the skull (Huss-Ashmore 1982).

Along with vitamin deficiencies, inorganic nutritional deficiencies will also compromise proper bone growth. Calcium and phosphorous are the most significant minerals involved in the growth and maintenance of the skeletal system. Calcium intake can be compromised by a variation of diet and environmental factors. Agarwal (2011) articulates the example of how a protein-energy rich and vitamin D deficient diet can affect the skeletal system, such as with the Inuit population and the evidence of decreased stature. The consistently low levels of vitamin D and calcium may cooperate to produce an anatomical behavioral change correspondent to skeletal remodeling or change.

This behavioral change would affect the overall consistent growth of the skeleton and inhibit proper bone growth processes pertaining to necessary nutrition for bone growth. Along with vitamins, protein is necessary to enable a healthy and successful growth process (Garn et al. 1969). Huss-Ashmore (1982:399) states that “a lack of protein can in turn materially affect the transport and utilization of vitamin A and calcium, further deranging the physiology of the organism, the level of nutrient provided in the diet is thus not necessarily the same as the level physiologically available.” Much of the function of metabolic growth can be attributed to the interdisciplinary component of dietary protein, specifically how much protein influences the various processes of overall growth.

Additionally, energy is significantly reliant on protein; thus, when the diet is restricted, non-dietary protein can be burned to provide necessary energy (Huss-Ashmore 1982:402). A lack of protein in the diet will affect every aspect of the nutritional growth process. Protein deficiencies are broadly systemic, affect energy, affect vitamin intake, stunt long bone lengths, narrow epiphyseal growth plates, and inhibit sites of bone formation (Frandsen 1954). Changes in the bone due to protein-energy deficiencies are the result of the destruction of bone matrix and decreased bone formation (McLean and Urist 1968).

Additionally, the weaning practices of a society can greatly affect an individual's growth post-weaning. There are few studies that have explicitly outlined juvenile cortical bone growth at Tipu; however, Hiers' (2014) study on isotopic analysis of weaning articulates the trends seen with cortical growth of the femur through isotopic analysis. Hiers (2014:58) explains, "Once weaning began around one year of age, the diet was increasingly supplemented with other foods until the process was complete, perhaps between the ages of two and three." The supplemental food was most likely a gruel made from maize.

Moreover, the individuals in the sample between three and seven years of age had average isotopic values slightly below the mean adult female value (ranging from 0.2‰ below the mean in the 3- to 5-year-olds to 0.6‰ below the mean in the 5 to 7 year old's) (Hiers 2014:72). These data suggest that the types of plants consumed by the adult females and young children may have differed, thus, emphasizing how growth seen in a juvenile population can be greatly influenced by the weaning practices.

When interpreting cortical area data, Huss-Ashmore (1982) implicated ideas pertaining to Wood's (1994) conception of the osteological paradox and the effect it can have on skeletal populations. Even if an individual is majorly vitamin deficient, an autopsy could come to a different conclusion due to how the illness may or may not manifest on the bone. Proper interpretation of cortical bone maintenance would entail a holistic approach to evaluating the skeleton. Huss-Ashmore (1982) emphasizes the analysis of the entire skeleton to narrow down possible causes of death.

To test this concept, Huss-Ashmore (1982) observed a skeletal series from a Nubian population and emphasized the use of cortical bone as a means of identifying deficiencies. When she compared femoral length correlated to dental age, it showed a relatively normal growth curve; however, cortical thickness in comparison to midshaft diameters had major discrepancies. The cortical thickness failed to increase with age in the population and actually decreased after the age of 10 (Hummert 1983:171). A healthy population will show a steady increase in cortical area from birth, but the Nubian population maintained the long bone growth at the expense of cortical thickness. Huss-Ashmore (1982:426) writes, "The percent of cortical area in the Nubian juveniles increases during the first two years of life and then declines sharply, despite fluctuations it is maintained at a relatively low level throughout childhood."

In general, the occurrence of premature osteoporosis in Nubian juveniles is linked to the demineralization of the bone from a lack of significant nutrients in the diet. Initially, Huss-Ashmore (1982:425) suggested the decrease in cortical bone could be evidence of a protein-energy malnutrition. However, the failure of cortical bone growth in the Nubian population is more significant to nutrient deficiencies rather than an absence of protein in the diet. Further histological analysis emphasized a pattern of growth and development that was correlative to bone loss related to a nutrient-deficient diet. Huss-Ashmore (1982:426) found “apposition of circumferential lamellar bone was maintained and was often the only cortical bone present, the ratio of formation to resorption spaces was determined with a small sample of each group.” Her results were consistent with Garn et al.’s (1966) study of bone loss in nutritionally related juvenile osteoporosis.

Analyzing the juvenile remains of Tipu with the application of Huss-Ashmore’s meticulous model of cortical bone growth and maintenance enabled a spectrum of perspectives on what may have caused an early death. Considering that nutritional deficiencies rarely occur in isolation; this idea should be applied especially to juveniles and how their early demise could represent a specific aspect of the population. An increased mortality of a certain age of children could be reflective of subsistence, and thus a specific sociocultural or environmental stressor affecting the population. Overall, the observation of cortical bone of juvenile remains reveals an important perspective of how such an early demise was possible in the society. In addition, cortical bone maintenance acknowledges disease and nutritional deficiencies but articulates the process of bone growth and development at significant times in an individual’s life.

CHAPTER IV - MATERIAL AND METHODS

In order to access the health profiles of juveniles at Tipu, the non-fragmentary femora were analyzed in juveniles aged 13 years and under. During the 1980s, the better preserved femoral diaphyses within the collection had been sectioned at the midshaft in order to evaluate cortical bone patterns, although no evidence of this research ever being carried out has been found. Among the 249 children in the Tipu population, 108 had femora sectioned at midshaft in the 1980s that were used in the present study. These individuals were then categorized into age groups using tooth eruption, beginning from birth to six months, followed by intervals of 1-2 years; sample sizes are given in Table 1.

Table 1 *Sample sizes by age.*

Age Group (y)	Sample Size
1	5
1.5	4
2	5
3	11
4	5
5	5
6	5
7	8
8	6
9	5
10	6
11	4
12	5
13	4

Cortical bone development was evaluated using both metric and imaging techniques. The specific measurements of the femur included maximum length of the diaphysis, which at times involved slight estimation of missing portions. Anterior-posterior diameter, medial-lateral diameter, and circumference of the external midshaft surface were also noted. Cortical thickness, which was the distance between the outer surface of the bone and the inner border of the medullary cavity, was recorded at the anterior, posterior, medial, and lateral aspects. All measurements were taken in millimeters using digital sliding calipers.

For the imaging evaluation, photographs were taken with a DSLR camera and with the bone contained in a lightbox to control lighting and enhance the structures and features. In order to avoid unnecessary shadows, the light was directed from superior to inferior. The image was taken directly of the face of the sectioned area. The image was then evaluated using the Stractec pQCT Image J with the plug-in area/fraction. It was used to measure the periosteal and endosteal widths of the cortical area of the femur and allowed for observation of cortical bone area, total area, and area ratio (Figure 3). "Area/volume fraction calculates the fraction of bone in an image by it to the whole thing. It counts all the foreground voxels, which it assumes represent bone, and compares them to the total number of voxels in the image. More formally defined, the plug-in in the case of a 2D image calculates the fraction BA/TA, which is area of bone per unit of the sample" (Doube et al., 2010:32). When I employed the area/volume fraction surface, the measurement standard was set at 1cm; in order to get the basic area and volume measurements, the image needed to be reduced to a more basic form of black and white to emphasize bone area to medullary cavity.

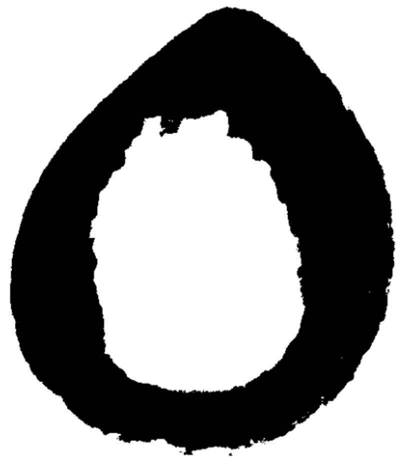

Figure 3. Example of Femoral Diaphyseal Cross-section Analyzed Using ImageJ.

The amount of bone mass interpreted from area measurements from the images along with the external measurements were determined for each individual. Mean values for each age group as well as well as a 3-year rolling average were calculated, and then compared across the established age groups. In addition, the data from juveniles at Tipu was also considered in light of Ubelaker's (1974) data of diaphyseal length in a number of other prehistoric New World populations. Findings were also compared with cortical bone patterns seen in Nubian groups as reported by Huss-Ashmore (1982). The correspondence of growth patterns across ages and across groups provided additional valuable information about the developmental status of juveniles at Tipu at the time of death. The results of this analysis are presented in the next chapter.

CHAPTER V - RESULTS AND DISCUSSION

The excavation of the cemetery at the colonial *visita* mission of Tipu provided a substantial amount of bioarcheological evidence of juvenile health using cortical bone analysis. Out of the 156 juvenile burials with measurable femora, I utilized 108 individuals with ages ranging from 0 to 13 who had relatively complete femoral diaphyses. Measurements of the diaphyseal lengths had previously been taken of the femora and were recorded in the files. For this study, four individual measurements were taken on each midshaft of the femur at the medial, lateral, anterior, posterior aspects of cortical thickness, evaluating the distance between the medullar cavity edge and the outside surface. In addition, each midshaft of the femur was used to measure the circumferential size as well as the anterior-posterior and medial-lateral size of the medullar cavity of each femur. The software BoneJ was applied to the images taken of the midshaft of the femora providing insight on the total cortical area. The average measurement was calculated in order to see potential trends across age groups.

Patterns of Diaphyseal Size by Age

Population-Level Analysis

As may be seen in Figure 4, the data articulated a general trend of growth with a gradual increase of growth from birth to 7.5 years of age, growth fluctuating after age 7.5, and steady growth picking back up around 12 years old. To put the diaphyseal lengths of the juveniles of Tipu in another perspective, given the small sample size and recognition that age determination was along a continuum, the rolling three-year average of the lengths associated with age group was calculated. The rolling average smoothed out the fluctuation of growth being seen with the general diaphyseal lengths from age 7 to 11 (Figure 4), showing gradual and consistent growth throughout juvenility.

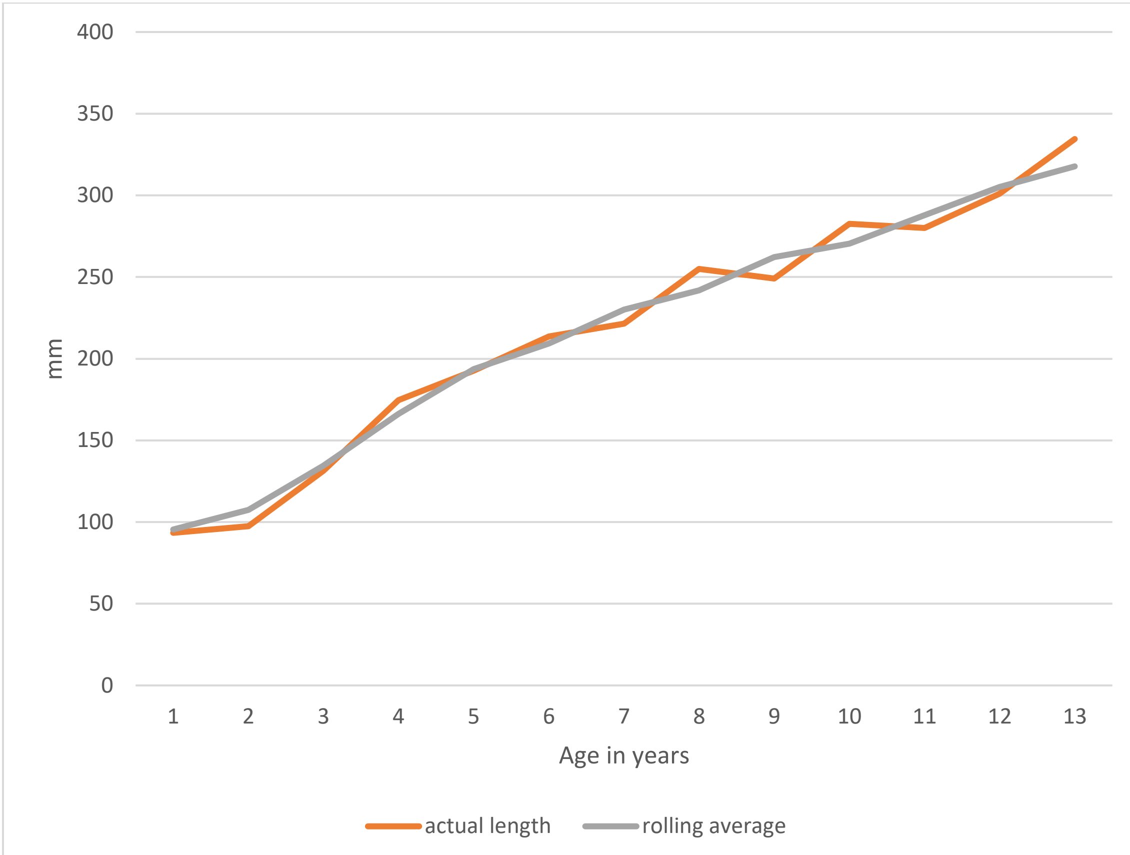

Figure 4. Mean Diaphyseal Length by Age: Actual Measurements and Three-Year Rolling Average

The circumferential midshaft measurements displayed growth in a similar trend (Figure 5). Among the 108 femora measured, overall juvenile growth using the raw measurements showed a general increase from infancy to teens. From birth to 2 years old, there was rapid growth, but after 3 years old, growth velocity decelerated slightly, and there are noticeable fluctuations, but steady growth could be observed throughout childhood. When the rolling average was considered, the rapid growth in the first few years of life was still evident, as was the steady incline of growth that observed through the circumference of the midshaft of the femur. However, the greatest velocity by a smaller margin was from birth until age 2. The fluctuation of growth, especially seen from 3 to 9 years old, was smoothed out.

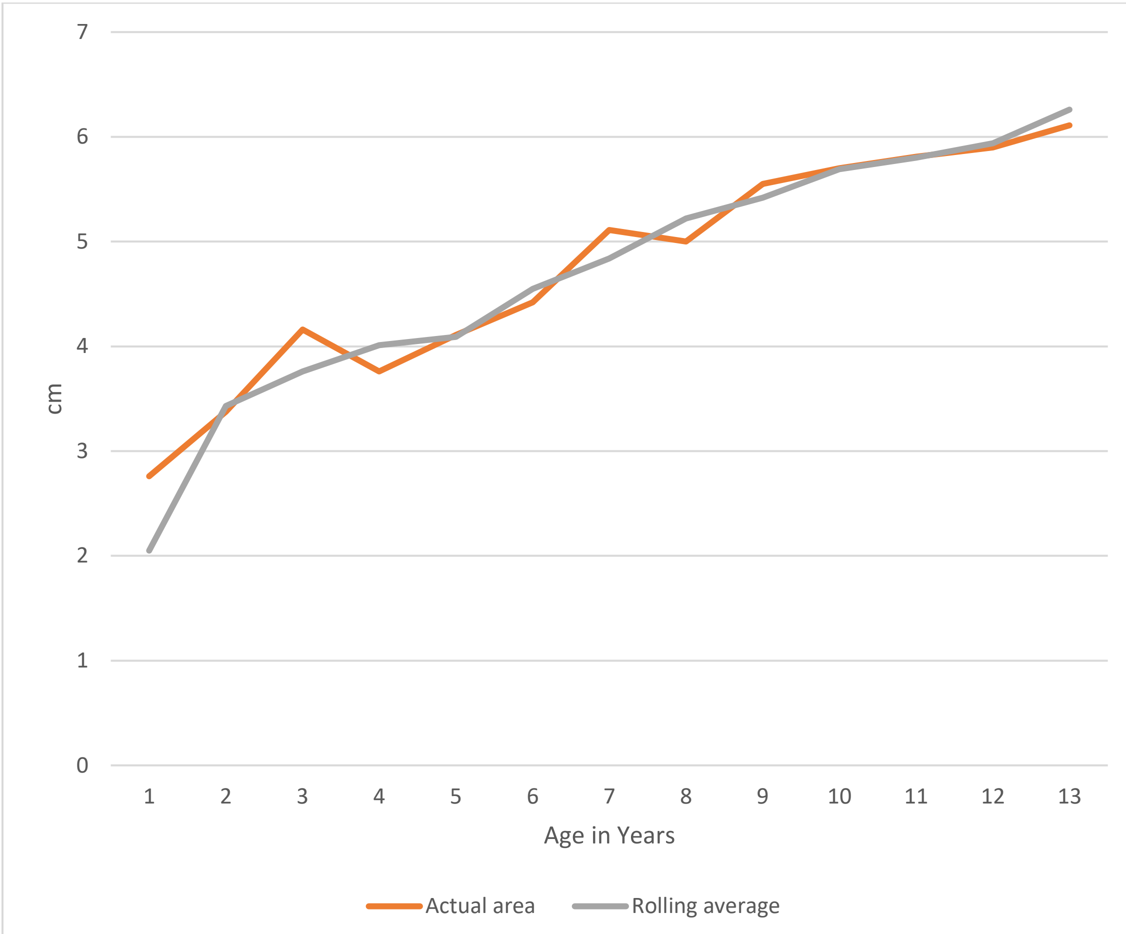

Figure 5. Mean Midshaft Circumference by Age: Actual Measurements and Three-Year Rolling Average

Figure 6 below represents changes with age in anterior-posterior and medial-lateral measurements of the medullar cavity of the midshaft of the femur. An initial acceleration of growth could be observed in both dimensions until about three years old. After that point, the anterior-posterior diameter increased at a faster velocity than did its counterpart. At age 10, the medial-lateral values especially began to flatten somewhat.

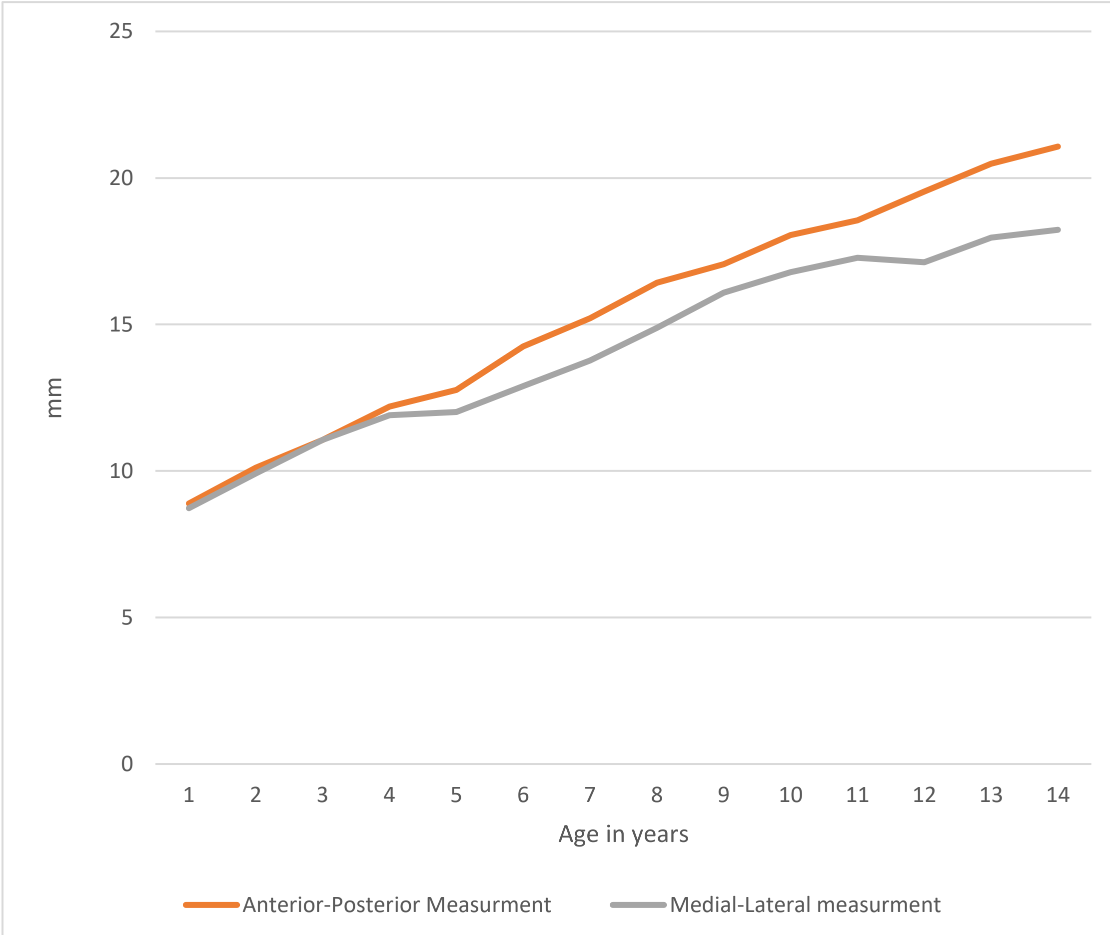

Figure 6. Mean Anterior-Posterior and Medial-Lateral Midshaft Diameters by Age in Years

The incline of growth in all dimensions, but especially midshaft circumference, from ages 0 to 2.5 can be accredited to a breastmilk diet full of nutrients and protein. During the first year of life, growth was substantial, and infants grew about 25 cm per year (Cameron 2002:22). Between ages 3 to 6, there was a smaller but still steady increase in growth in the population, which also fit expected patterns. Cameron (2002:28) explains, “After the third year, there is much milder decay in velocity during school years before the adolescent growth spurt.” This time also equates well with the period Bogin

(1994:29) defines as childhood, which is “the period following weaning, when the youngster still depends on older people for feeding and protection. Childhood ends when the growth of the brain (in weight) is complete; a recent morphological and mathematical investigation shows that this occurs at a mean age of 7 years.”

After childhood, the juvenile growth period takes place when the child is no longer dependent on others but is still prepubertal (Bogin 1994:31). During this phase, mean peak height velocity is approximately 9.5 cm/year in boys and 8.5 cm/year in girls; children become entirely dependent on a non-breast milk diet which is often lower in quality, especially in protein (Bogin 1994:31). This period at Tipu, however, was not marked by any significant change in the trajectory of either diaphyseal length or midshaft circumference.

Additionally, at this growth stage, independence becomes significant to assuming economic roles. Bogin (1999:119) emphasizes the unique capacity for learning in humans and how experience and observance benefit survival, especially during the juvenile growth period. The juvenile growth period enables learned independence through observation, and juveniles are exposed to economic responsibilities (Bogin 1994:31). Although limited in their contribution, juveniles learn skills related to food production and are involved with familial responsibilities (Bogin 1994:31). In this case, nutritional supplement usually takes place since some minor responsibility for subsistence practices would likely be assumed (Graham 2011). Tipu demonstrated the expected patterns with steady increases in both dimensions for this age period.

Bogin (1994:31) argues that the juvenile period ends about age 10, correlating to the onset of puberty and the adolescent growth period, specifically when we see both sexes have spurts of growth in both height and weight. At Tipu, ages 11 to 13 showed an incline of diaphyseal length growth that was somewhat more evident in the raw values rather than the rolling average trend. Bogin (1994:29) explains during the adolescent period, further adoption of adult patterns of economic behavior usually occurs. The 11- to 13-year-old girls might have begun to consume more non-maize food and less protein than the boys. Harvey (2011:87) writes, “There was probably no differential access to food or male favoritism at Tipu, yet the symmetry of health profiles of the sexes can be attributed to continual access to resources from two economic spheres.” Even prior to the adolescent period of growth, girls during childhood were likely getting involved in food preparation and procurement, leading to their diet of a variety of nutritional supplement other than maize such as foraged nuts and berries; boys would likely be exposed to learning to hunt and experiencing more protein in their diet (Graham 2011). This notion could also help to explain the steady growth observed throughout the adolescent period.

Differences in Diaphyseal Length Growth for Burials Inside and Outside the Church

In an intrapopulation comparison, those individuals buried inside and outside the church may represent a difference in cultural treatment related to status, which would potentially include varying access to nutritional resources. Jacobi (2000) notes there are no genetic nor health differences observed among the burials in the two areas of the cemetery. However, he also emphasizes Catholic burial practices that involve preparations of the body as well as “status-religious, economic, or that due to some other attainment-generally determined burial placement” (2000:26). Jacobi does argue that juvenile burial placement most likely followed the traditions of the Catholic church: “First interments were within the church with these inside burials continuing until overcrowding forced mourners to bury the deceased in outside graves," although Musselwhite (2011) found no differences in fluoride levels in burials that would suggest such a pattern. Figures 7, 8, and 9 articulate the differences in bone measurements observed between the inside and outside juvenile burials.

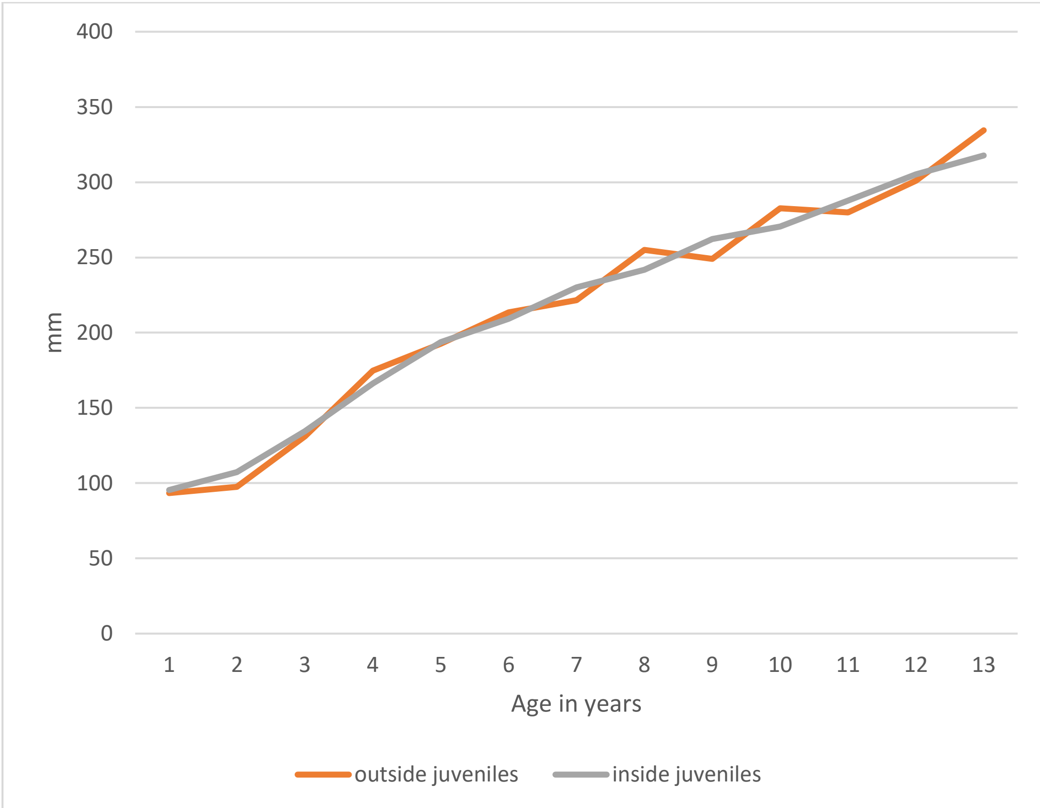

Figure 7. Mean Diaphyseal Lengths by Age for Juveniles Buried Inside and Outside Church Nave.

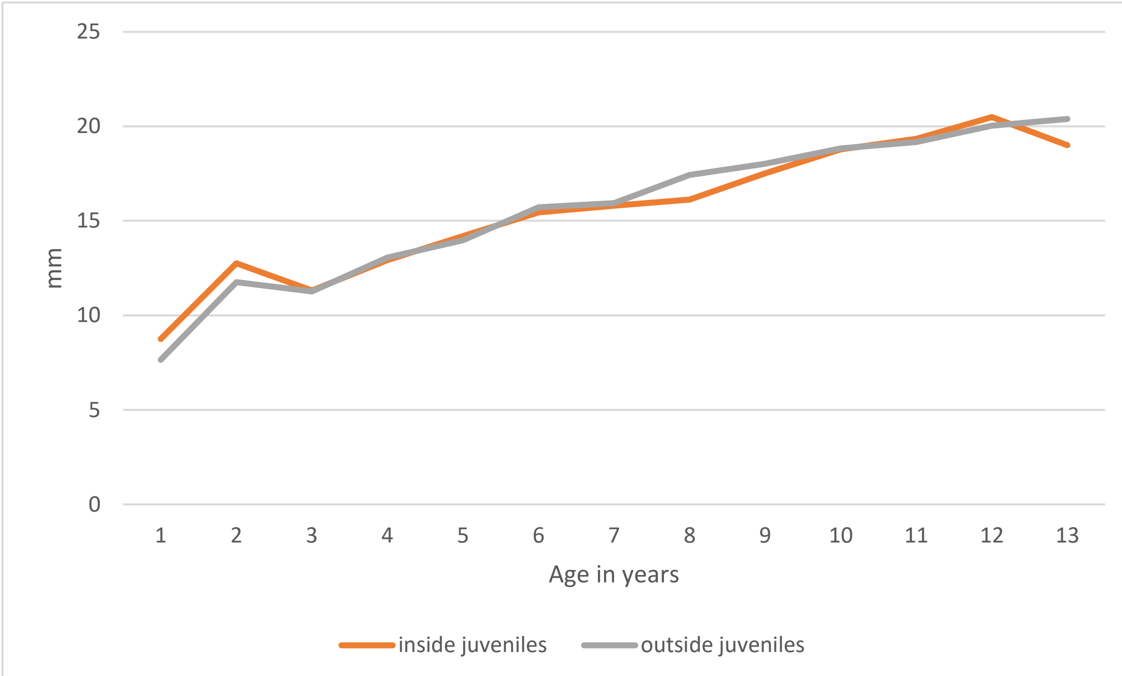

Figure 8. Mean Anterior-Posterior Midshaft Diameters Age for Juveniles Buried Inside and Outside Church Nave.

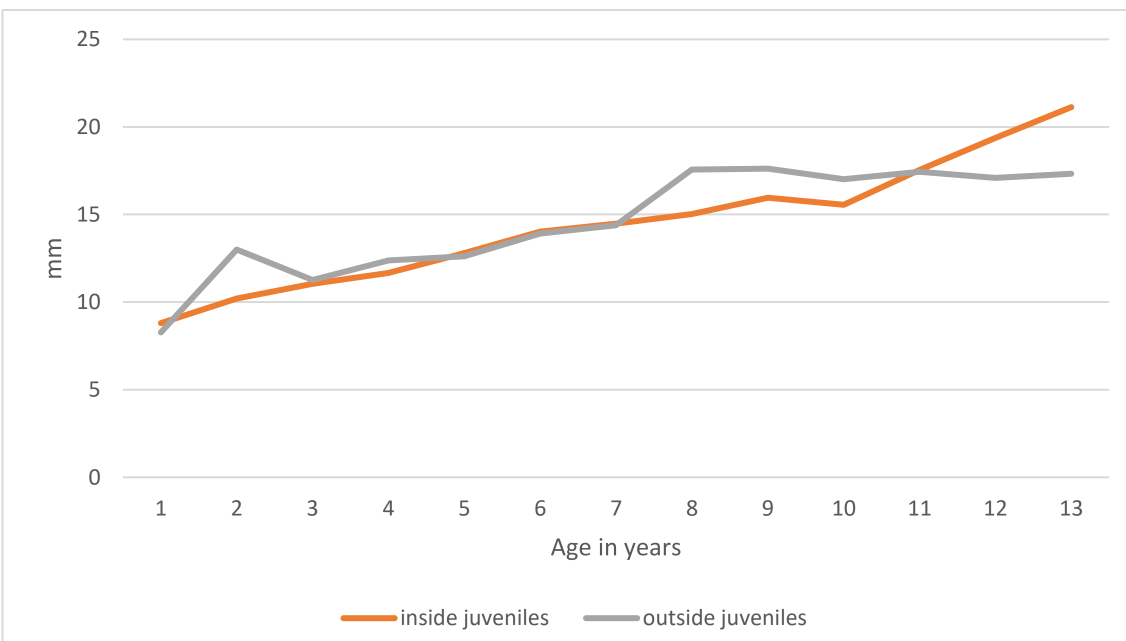

Figure 9. Mean Medial-Lateral Midshaft Diameters Age for Juveniles Buried Inside and Outside Church Nave.

However, as may be seen in Figure 8 and 9, it was evident that the difference of the circumferential growth patterns among the juveniles excavated both inside and outside the church that the subadult individuals buried inside the church display greater bone development at nearly every age, especially after age 3, compared to those buried outside the church. By nine years old, the difference in cortical area reached about 15 to 20%. The same pattern, however, was not seen in diaphyseal growth. Juvenile burials found outside the church displayed about the same in increases to the diaphyseal length and circumference of the midshaft of the femur as compared to the juveniles buried inside (Figure 7).

It is possible some preferential treatment took place with juvenile burials that resulted in more nutrient-rich food resources, specifically in the case for those interred inside the church at Tipu (Jacobi 2000:171). However, the conclusion of more compromised growth of those interred outside the church was also not supported by other markers. Jacobi (2000) discusses that the burials found both inside and outside the church lack any significant health discrepancies. The occurrence of trauma, presence of skeletal infection, or observation of linear enamel hypoplasia and scurvy were all low for burials found both inside and outside the church. The only difference seen was that adult individuals buried at the front of the church, male or female, experienced a higher rate of trauma than those found in the back of the church (Jacobi 2000:173). Therefore, the individuals in the church nave were likely not different in their economic status compared to the others.

Comparison with Other Prehistoric Populations

To gain further insight into conditions at Tipu, the diaphyseal lengths of juveniles at the site were compared with those from two coastal Postclassic Maya sites. San Pedro and Marco Gonzalez, found on Ambergris Caye, exhibited similar growth curves with the juveniles seen at Tipu. In her study, Bleuze (2007) looked at whether the presence of health stress markers affected the juveniles' femoral diaphyseal length. She found that "femoral lengths for age-matched infants and children regardless of health status do not differ greatly; these results may suggest that the proximal lower limb segment, unlike the proximal upper limb segment, may be less affected by health stress, particularly in populations that are not experiencing a downward trend in stature as an adaptive response to adverse conditions" (2007:78).

As may be seen in Figure 10, when Tipu's data was compared with the growth patterns from the two sites from Ambergris Caye, patterns were very comparable, especially considering the minimal sample size of the latter (N=9). Although Bleuze found very slight growth differences between children who had and did not have pathological markers on the bone, Tipu's growth curve danced between them along their lengths without any consistent pattern of difference. In all of this analysis, however, it is important to remember Bleuze's observation that a lack of pathological markers may simply mean that the child did not survive long enough for physiological disruption to affect skeletal growth.

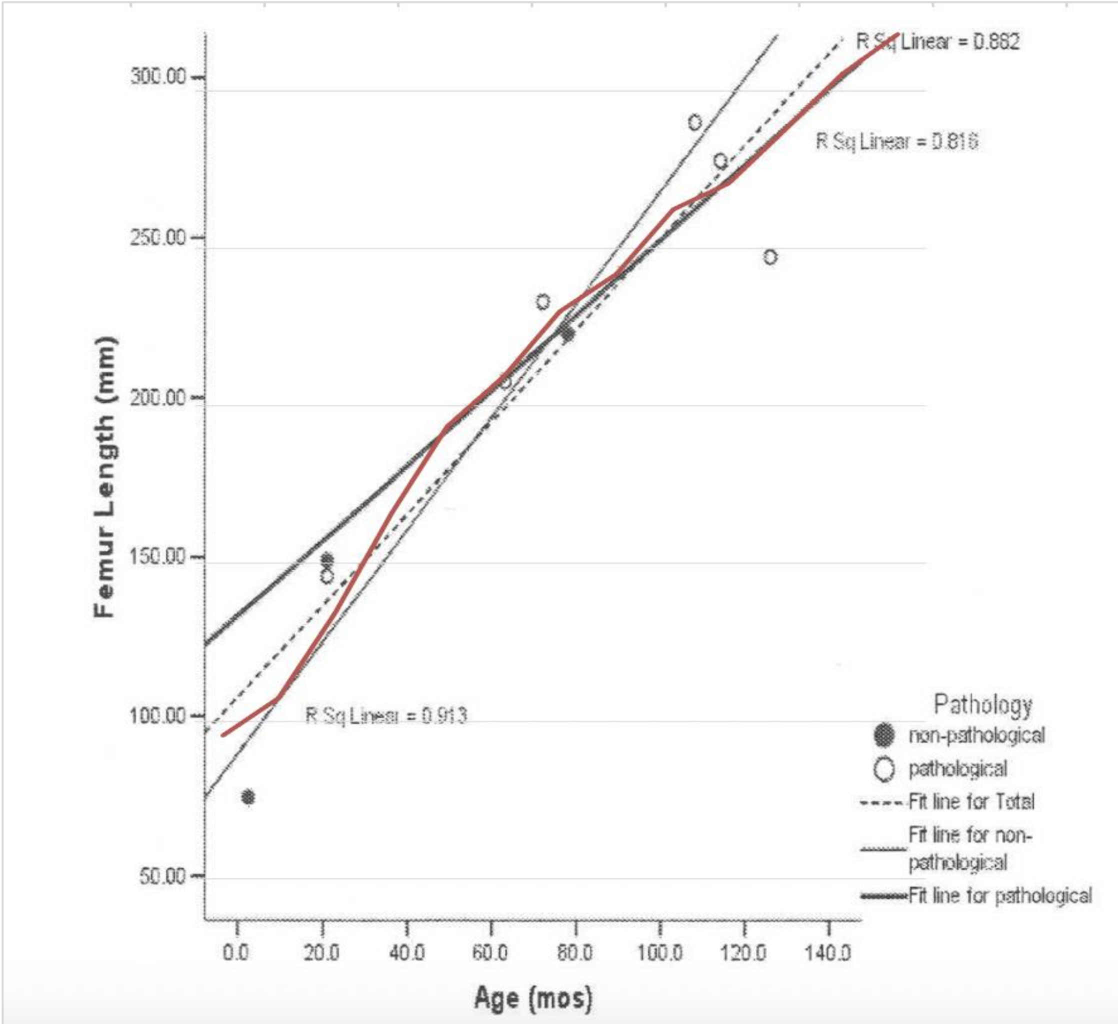

Figure 10. Femoral Length by Mean Age at the Tipu and Ambergris Caye; Tipu Data is Noted in Red. (Adapted from Bleuze 2007:71).

In a broader consideration, Tipu's findings were examined in light of Ubelaker's (1974) analysis of other New World populations. He investigated growth curves of diaphyseal measurements for six prehistoric populations, including modern Eskimo/Inuit, Archaic populations from Kentucky (Johnson 1962; Sundick 1972), protohistoric Plains groups (Merchant and Ubelaker 1977), and a Late Woodland group from Indiana (Walker 1969). Figure 11 exhibits the Tipu juvenile diaphyseal lengths in correlation with these groups.

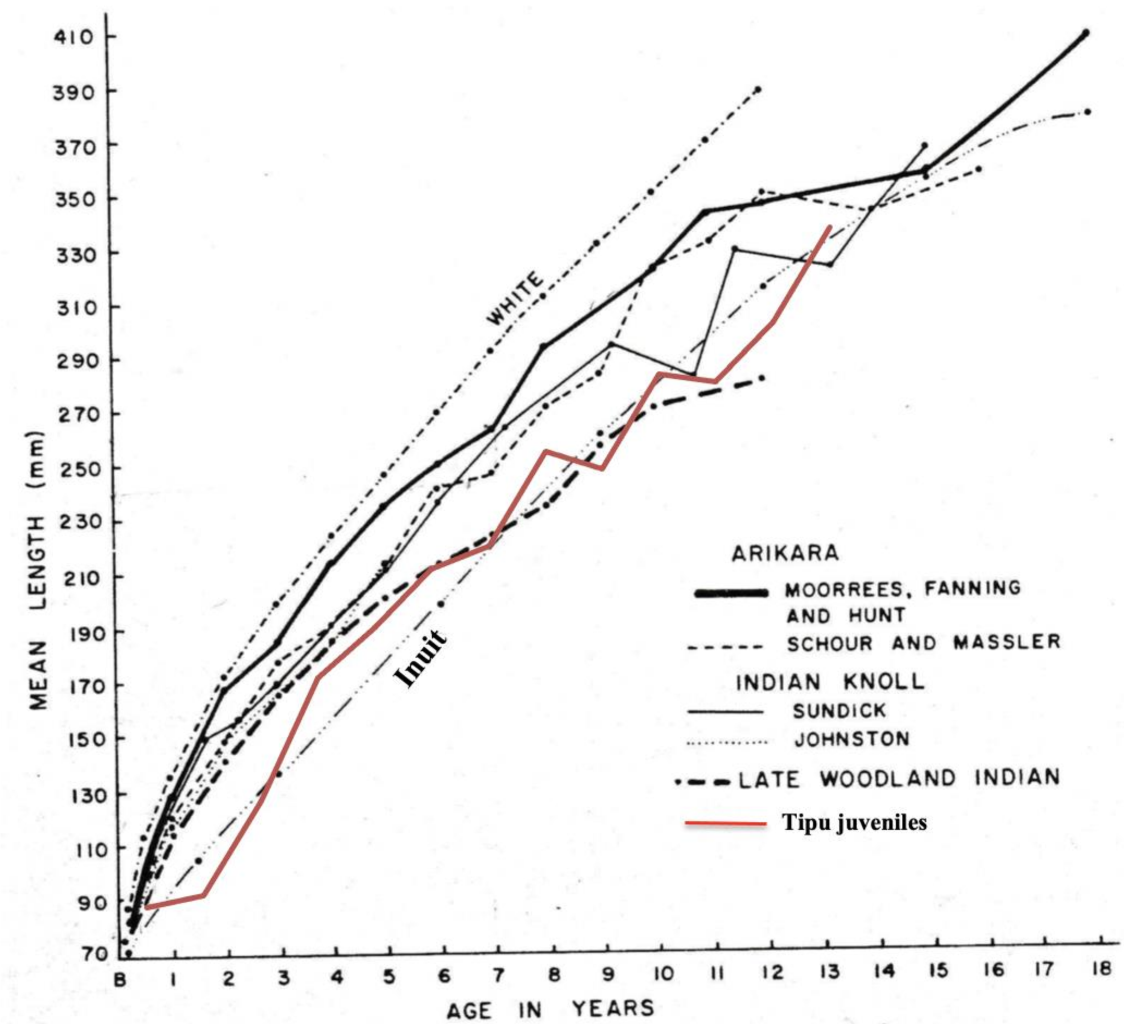

Figure 11. Mean Diaphyseal Length by Age at Tipu Compared with Other Prehistoric New World Populations (Ubelaker 1974).

As may be seen, the diaphyseal growth trend in the femora expressed by the Tipu juveniles was very similar to all of the growth curves except for the Inuit up until about age 4, when weaning would have been complete for each population. Again, the breastmilk diet likely enabled this spurt of growth seen in the ancient populations. After that age, the growth curves began to diverge, with Tipu juvenile diaphyseal measurements being most comparable to those seen in the Late Woodland Indian and

Inuit populations. Growth steadily also continued in all of these groups after young childhood, but not at the greater rate characterizing Whites, Arikara, and Indian Knoll.

Most likely, these differences in femoral growth measurements are due to access of resources and subsistence practices. Maize was a significant form of nutrition for the inhabitants of Tipu, and the Late Woodland group from Indiana was transitioning to maize dependency (Merchant and Ubelaker:1977). Hiers (2014:58) and Tozzer (1941) recognize the main weaning food of the Maya was a maize gruel, which also was possibly true for the Late Woodland group. Additional nutritional supplements were also likely introduced at Tipu, such as squash, beans, and faunal remains indicated animals, birds, and fish that added to the diet (Jacobi 2000:18; Graham et al. 1989:1255). However, they probably still did not offer as much of a balanced diet as the Archaic and Plains groups, who most likely followed a hunter-gatherer subsistence pattern in which nutritional resources, especially protein ones, might have been more diverse and accessible (Ubelaker 1974).

In summary, the diaphyseal data emphasized a juvenile population experiencing a normal growth pattern in correspondence to age, albeit they were generally short individuals. It suggested a fairly well-fed juvenile population despite a primarily maize-based diet. The lack of pathologies supported there were no severe or chronic nutritional deficiencies commonly present. The difference in midshaft circumferential data of the individuals buried inside the church nave versus outside might suggest a juvenile population with varying access to nutritional resources or other differentiation in economic treatment. Still, the differences were slight and additional support was not to be found in patterns of other health markers observed in the population.

Cortical Thickness Measurements

Four measurements of cortical thickness were taken around the medullar cavity of the midshaft of the femur; the first point of measurement was on the landmark the linea aspera, and three points reflecting the medial, anterior, and the lateral aspects. As may be seen in Figure 12, each measurement point expressed very slow, if any, growth from ages 0 to 5, but a distinct spike in growth occurring after five years old. At this age, growth began to pick up markedly, with a particular spike at age 12. All the points of measurement around the medullar cavity showed a similar trend of growth but varying in the specific increase of growth at particular ages. However, at age 4, the linea aspera growth began to escalate. The significant growth observed with the linea aspera was likely related to muscle strength increase during the growth development period from childhood to adolescence (Gillian et al., 2018:3). In comparison, the medial and lateral thickness were most similar in the trends of growth.

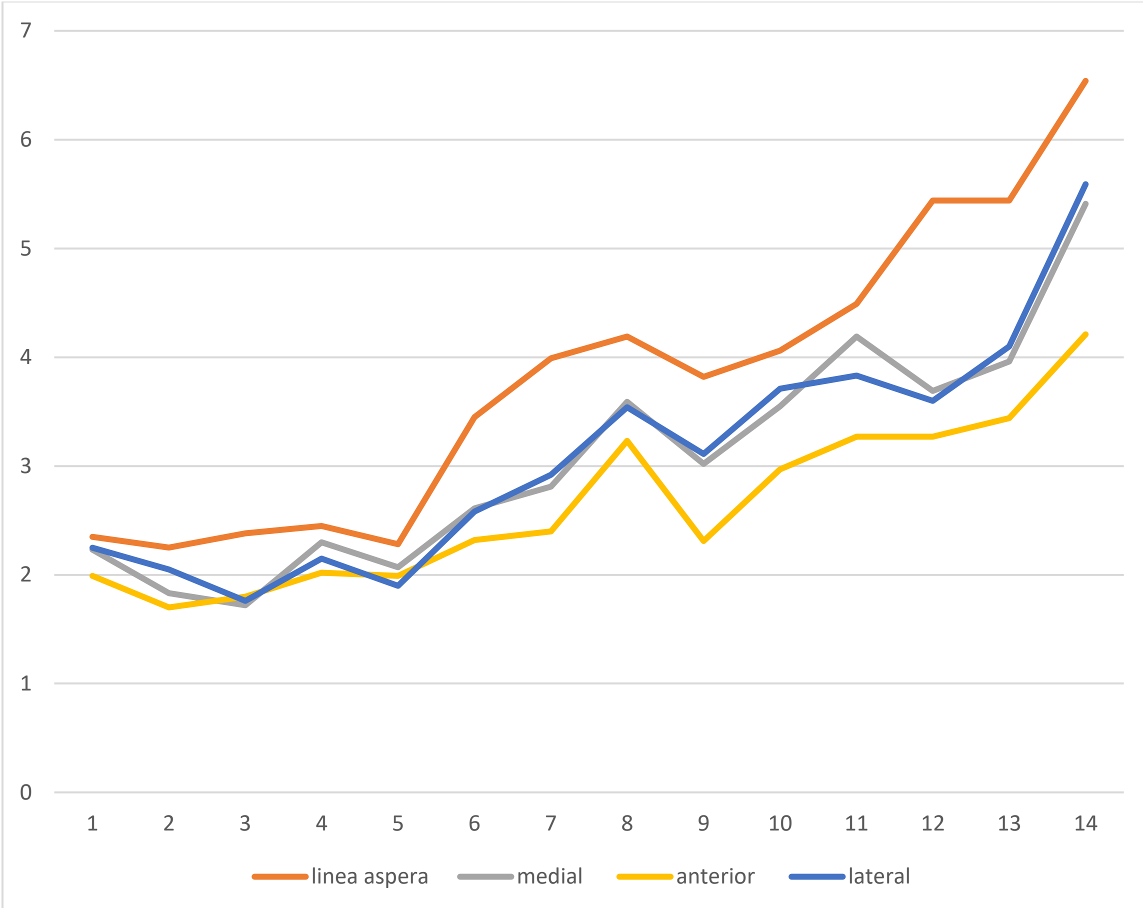

Figure 12. Mean Cortical Thickness by Age at Specific Points Around Femoral Midshaft.

Discussing the period from early childhood (3-5) to middle childhood (6-11), Gillian (2018:3) notes, "During this period, skeletal muscle also undergoes morphological changes, leading to increases in muscle size." Muscle mass increases regardless of the muscle group, showing a significant increase during this developmental transition. From birth, three types of muscle tissue development begin and increases in tandem with bone growth, and maximum muscle strength is achieved at 25 and decreases thereafter (Peate and Gormley-Fleming 2021:367). At Tipu, the linea aspera by far showed the most increase in growth, and the anterior point of thickness had the least increase of thickness over time, especially after age 4. This was most likely related to the linea aspera being a point of muscle attachment for the hamstring muscle group.

Comparison with Other Populations

The mean midshaft total diameter and cortical thickness measurements at Tipu were also examined in light of those seen in ancient Nubia. Huss-Ashmore (1982:427) observed that the total midshaft diameter continued to exhibit steady growth in the Nubian sample, but the anterior cortex thickness exhibited a decrease after the age of 10, as may be noted in Figure 13. In contrast, the Tipu juveniles, represented by the red line, exhibited a spurt of growth from birth, as was also seen in the Nubians. However, midshaft diameter at Tipu after age 4 continued to increase at the same velocity, gaining diameter at a much larger rate than the Nubian juveniles and somewhat following the same pattern as seen in the diaphyseal length comparison. The anterior cortical thickness among the Tipu juveniles, indicated by the blue line, also showed more consistent and gradual growth than the Nubian juveniles.

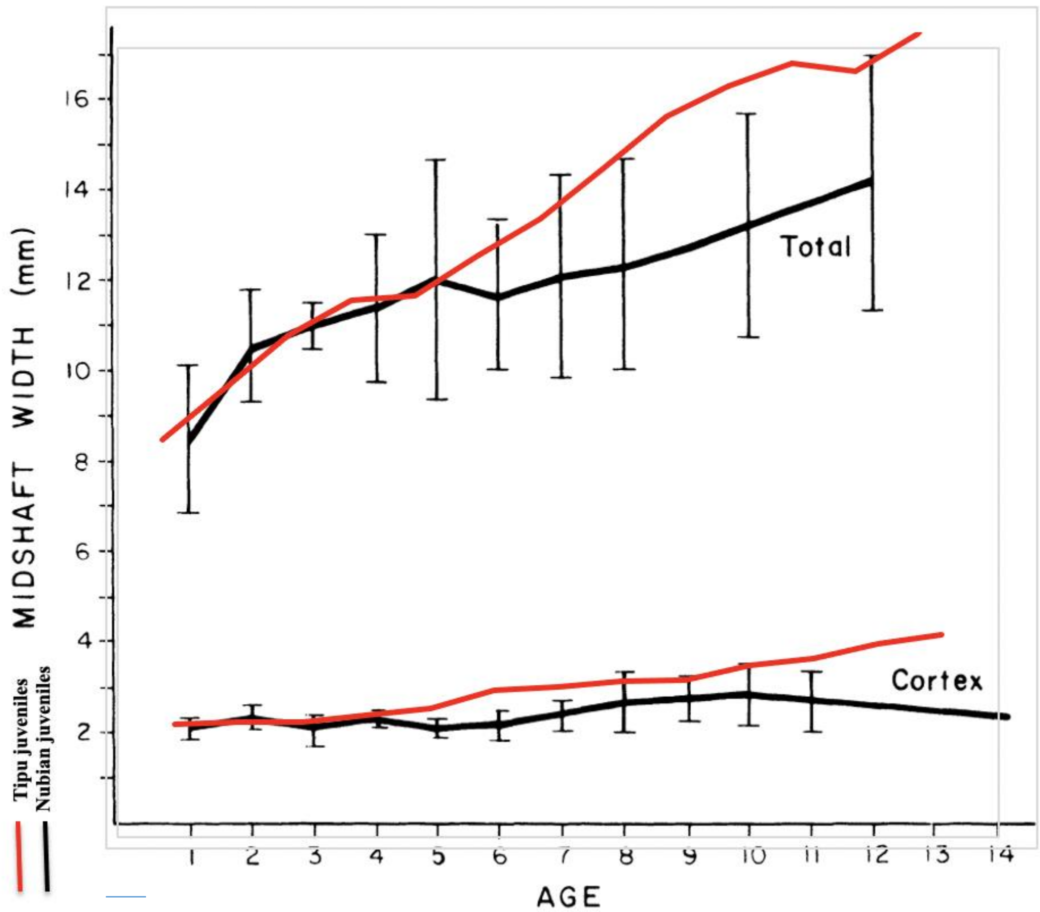

Figure 13. Mean Midshaft Length and Anterior Thickness of Cortex by Age at Tipu and Nubia.

Tipu also maintained a more consistent increase in femoral diaphysis length compared to the juveniles from Nubia (Figure 14). Interestingly, they were noticeably shorter until ages 5-6, but then surpassed the Nubians even though the Maya are generally regarded as a relatively small-statured population. This was also the same age at which the cortical thickness values between the two populations started to diverge.

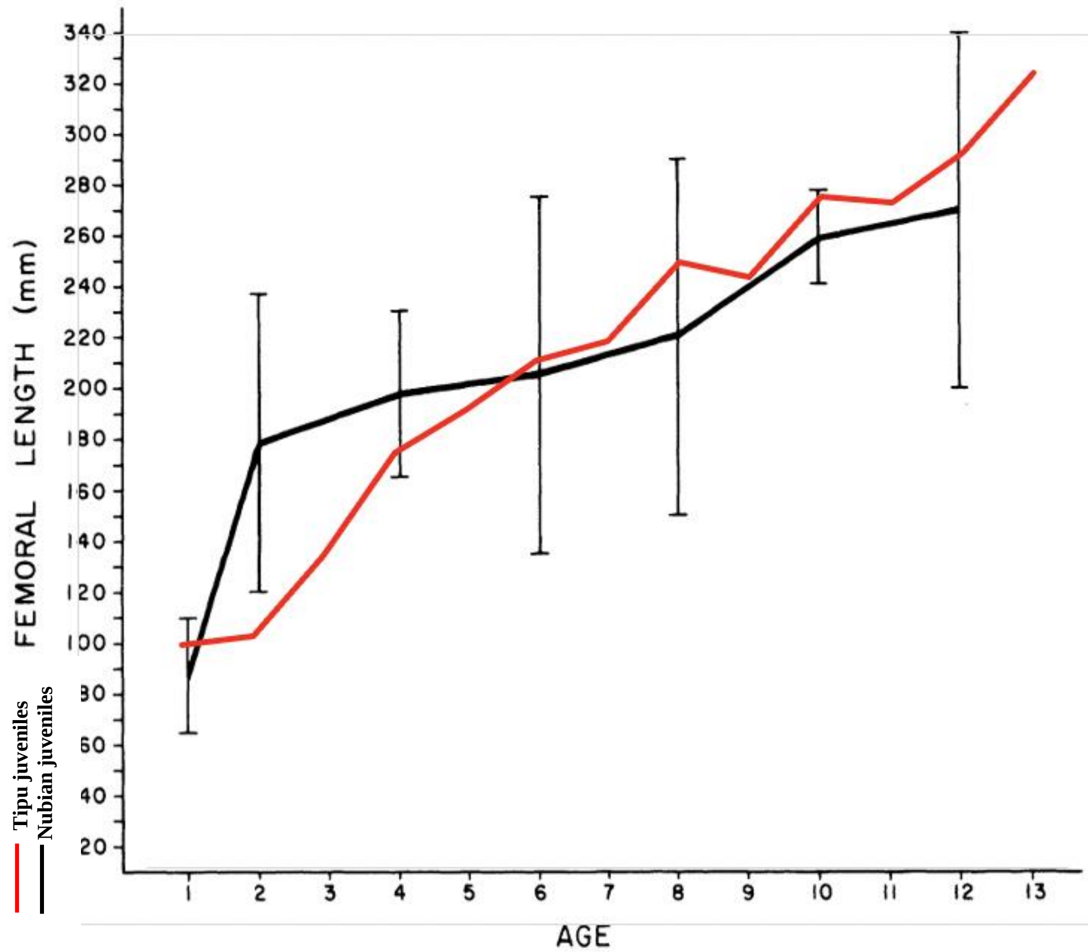

Figure 14. Mean Femoral Diaphysis Length by Age Among Juveniles in Nubia and at Tipu.

Huss-Ashmore (1982) argues that the Nubian results show that midshaft growth was maintained at the expense of cortical thickness. She also concludes this premature osteoporosis occurring with both infants and children may be caused by nutritional deficiency but also may be related to the adult females experiencing high stress at peak reproductive period in correlation to diet (Huss-Ashmore 1982:429). This implies the Nubian women's health status affected the outcome of the child's health and compromised growth patterns. Regardless of the specific cause, neither situation appears to have been occurring at Tipu, considering that both midshaft width and cortical thickness both increase with age.

In contrast, findings at Tipu were more similar to those seen in a modern Guatemalan juvenile population. Himes et al. (1975:35), using x-rays of femora, obtained cortical thickness through subtraction of the medullary diameter from the periosteal diameter. They found that there was a general increase in growth with cortical thickness from ages 0-7 with juveniles. The researchers explain that although the Guatemalan children experienced relatively standard growth rates, the presence of protein-calorie deficiency in correlation to the environment affected the growth outcome (1975:367). Despite the major differences between an ancient and modern population, the environment was correlative to both populations, especially in terms of subsistence, and likely explains the similarities of growth curves.

Cortical Bone Area with ImageJ

To further my analysis of the cortical bone beyond the data gained from calipers and measuring tape, the image-analyzing software BoneJ was used to provide measurements of the cortical bone area, total midshaft area, and area ratio. In order to access these measurements, a 2D DSLR image taken face-on of the midshaft of the femur was uploaded for further analysis. The software plug-in allowed for volume/area fraction measurement of the bone areas.

Five sectioned femora were used to represent each year age group as a way to gain data to compare with earlier analyses. A larger number could not be analyzed due to the number of images that were in sufficient quality for the ImageJ analysis tool to operate. Each image used was analyzed three times, and an average for each measurement was made using the results of the three analyses. As seen in Figure 15, the results expressed similar trends seen cortical bone area, total area, and bone area ratio, specifically a general overall increase; however, the spike of growth during the first few years of life associated with the breastmilk diet was not as prominent here.

The data represents a population that is still exhibiting steady growth in the total bone cross-sectional area from birth to 7 years old, followed by a plateau at an age. Bogin notes there often is a slowing of growth compared to younger years. Then a resurgent growth increase around age 11, likely correlating with puberty (Bogin 1994:22). The total bone area similarly increases, although at a slower rate, and there is a flattening of the curve around ages 10 to 12.

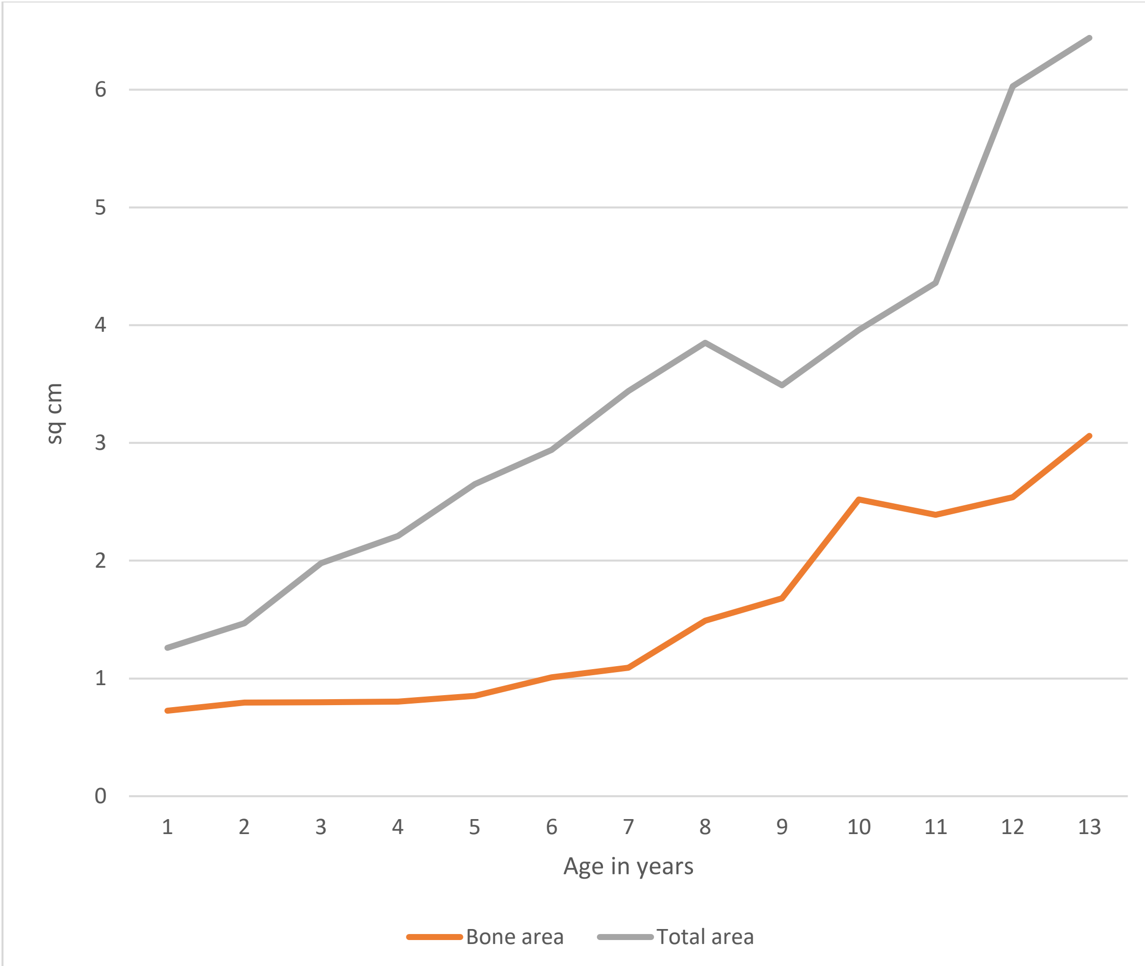

Figure 15. Mean Total Midshaft Area and Cortical Bone Area Determined by BoneJ by Age in Years.

Although the data exhibited the expected pattern, there are concerns about its reliability. The main issue with the use of DSLR 2D photos with the BoneJ software is the lack of precision in the tools to access the total cortical area. Figure 16 helps to illustrate the process of preparing the image to a binary format to enable BoneJ analysis. In order to get the most precise image for analysis, it was necessary to apply the freehand selection tool in order to edit and crop out the specific area of the medullary cavity; if this was not done, the image potentially could include more area for analysis when made binary, thus affecting the accuracy of the outcome of surface/volume analysis.

Additionally, the younger juveniles had thin cortical bone, making it much more necessary to meticulously and precisely outline the external and internal edges of the medullary cavity in order for the BoneJ plugin to provide accurate analysis. Specifically, in order to isolate the bone in the image, one must crop and erase the non-bone part of the image. This proved very challenging regardless of how enlarged the image was made and how strong the clarity might have been. Figure 16 illustrates the editing process of achieving the most accurate results for BoneJ to analyze but also reveals the possible discrepancies when not editing precisely.

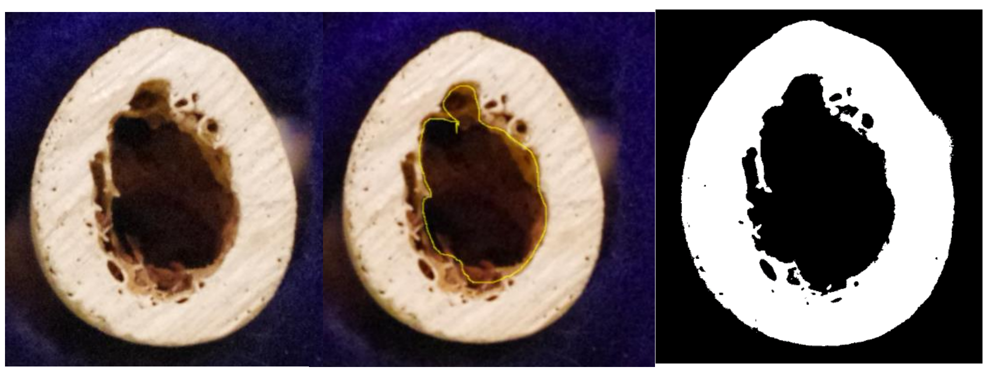

Figure 16. The Image Editing Process for Bone J: Left, the Initial Unedited Image; Middle, the Outlining Tool (Yellow) Used for Precise Cropping; and Right, the Binary Image Product.

It is possible that juvenile bones photographed with a DSLR camera may not be the most accurate option for bone observation. Still, a sample size larger than five per age group might have been able to help to average out inconsistencies in the data being analyzed. However, despite the issues I experienced with the ImageJ software, I was able to gain additional data providing context for bone area enabling alternative comparison for other ancient juvenile populations. Still, its specific reliability cannot be guaranteed.

General Health Patterns of the Juvenile Population as Observed Through Analysis of Cortical Bone

In general, my results of juvenile health patterns at Tipu suggested by cortical bone growth were supported by those seen in previous studies of the population (Bianchi 2020; Cohen et al. 1994, 1997; Gomberg 2018; Harvey 2011). In examining the diaphyseal bone size, all four measurements (diaphyseal length, circumference, anterior-posterior diameter, and medial-lateral diameter) displayed relatively similar trends. Overall, the data showed a steady consistency of cortical bone growth of the femur and there were no differences by burial location. Thus, none of the three hypotheses of the study were strongly supported despite the presence of a maize-based diet in the population.

Each measurement indicated an initial spurt of growth starting at birth, likely due to a breastmilk diet. By age 2, the effects of weaning seemed to manifest more with cortical thickness rather than circumferential growth, considering the more apparent deviation in growth during this growth phase. Jones (2000:25) analyzed modern populations for bone mineral density and observed that children breastfed for a longer time had a strong correlation to higher bone mass values and resulted in significant long-term effects, specifically with the adolescence phase which 90% of peak bone mass is attained. This concept is supported by the evident feeding practices at Tipu where juveniles were weaned by the start of the childhood growth period (Hiers 2016).

However, there was a decrease in growth velocity during the ages of 2 to 6 years at Tipu. Discussing the Nubians, Huss-Ashmore (1982:412) writes, “Because weaning … is frequently accompanied by infection and refusal to eat, we hypothesize that this growth pattern reflects acute nutritional stress. Such stress should be most obvious in areas where suitable weaning foods are absent or low in protein." Considering the subsistence resources available to the Tipu Maya, Huss-Ashmore's hypothesis might apply here too.

Although bone dimensions continued to increase after weaning, albeit, at a somewhat slower rate, the only noticeable fluctuation appeared to occur from ages 6-9. This may be due to the biological changes taking place and the initiation of learned economic participation. Bogin (1994) describes a small increase in height velocity during the juvenile period, followed by a plateau of growth during this period. Similarly, the juvenile age group (ages 6-9) of Tipu showed a similar rate of height velocity with a slight decline in height velocity as well. After this age group, Bogin (1994) argues a sudden and rapid increase in height with the onset of the adolescent period is a standard pattern for this age group. This notion is applicable to the Tipu juvenile adolescent group. This height velocity acceleration could be seen after age 10 in every form of measurement presented with the Tipu juvenile population. In general, the Tipu juveniles' health patterns maintained a standard rate of growth in all aspects of acquired measurements, and especially when compared to other growth curves of ancient populations.

Since these measurements represented a juvenile population with access to necessary nutritional resources, there is still the mystery as to why these children at Tipu died so early, considering their generally healthy skeletons left behind. As (Bleuze 2007:75) notes, although there may not be evidence of major health and growth disruptions, the fact that a sub-adult did not survive to maturity emphasizes the unusual nature of the individual's death, especially if there was a lack of any skeletal evidence.

However, the cortical bone evidence suggested that these children were able to experience life at contact period site without evident chronic malnutrition.

CHAPTER VI - CONCLUSIONS

The purpose of this study was to evaluate the health of juveniles at a contact Maya site using cortical bone growth patterns. The diaphyseal length, as well as midshaft transverse measurements, were analyzed in 108 individuals from birth to 13 years of age. The Tipu juveniles were revealed to be a generally healthy group with evidence of standard growth and cortical thickness development patterns. The juveniles exhibited the fastest bone increase after birth until age 2. Post-weaning, growth began to slow down but increased again at the onset of puberty. Despite contact with the Spanish missionaries and maize as their primary subsistence staple, the Tipu juveniles followed expected patterns of growth in correlation with social and economic developments concerning childhood.

In specific discussion of the hypotheses tested: initially my first inquiry was that Tipu would have longitudinal and transverse bone dimensions that would increase with age in patterns comparable to those seen in other populations, although Tipu would be shorter. Second, that Tipu would not display premature osteoporosis as indicated by longitudinal growth at the expense of cortical growth. Finally, that Tipu would have total cortical areas that would increase with age in a pattern comparable to those seen in other populations

In general, the Tipu juveniles exhibited longitudinal and transverse increase in bone dimensions, especially when compared to other juvenile populations. Additionally, the Tipu juveniles were generally shorter in stature in those comparisons; the juveniles also showed no signs of premature osteoporosis considering the cortical thickness grew at a standard rate when compared with diaphyseal length. Furthermore, the cortical area of the Tipu juveniles exhibited consistent growth when compared to other juvenile populations

Despite the fact that the skeletal evidence using cortical bone data may not represent poor health and irregular growth, we must also acknowledge these juveniles did not survive to maturity, and the cause could have been health-related, but the health disruption may not have had time to manifest between the time of appearance and the time of death. This was still a mortality sample being investigated.

Reflecting on possible issues with analysis, taking physical measurements of some of the bones was difficult due to some of the bones having compromised measurable area, usually from breakage. Also, infants and young children at times had such small bone area it made it difficult to be precise, even with digital calipers. In addition, although the juvenile sample size of Tipu is quite large, some age groups were lacking in observable femora. Having a larger sample size in general, but specifically for certain age groups, would have enabled an even more reliable and in-depth analysis of the juvenile segment of the population.

In general, I believe the results of my study further support existing observations on Tipu, adding support to the minimal number of studies that have been conducted thus far on the lifeways of children at the site. However, the investigation makes further contributions in a number of ways. First, it shows the potential value of examining cortical bone in children, which is especially revealing in those populations that have a diet based on a staple such as maize that is deficient in many critical nutrients. Second, although Tipu is a contact period site, the continuation of earlier lifeways allows it to serve as a proxy for ancient Maya juveniles of the Postclassic period as well and possibly even earlier. Third, it was one of the first applications to assess the potential role of the software BoneJ to offer more precise metrics to the research. Although the measurements provided by BoneJ's assessment generally correlated with the patterns of the cortical bone growth seen at Tipu as indicated by physical measurements, the software presented many challenges that did not make it easy to use with juvenile bone, especially those of infants and very young children.

Although analysis conducted in this study further supported the notion of a generally healthy Maya population at Tipu, more in-depth analysis of the juvenile cortical bone gained through imaging techniques used in medicine to get even more precise perspectives on the cortical bone. Additional inquiry into the cortical bone of the Tipu juveniles, especially with C-T or X-ray images, might be able to identify underlying negative health factors that were otherwise unobserved through the methods used in this study. Additionally, a more in-depth analysis of how to best apply BoneJ to more easily gain the information it can provide would be helpful, and could provide an alternative perspective into the bone but would require C-T, X-Ray, or 3D imaging, in general, to gain that more detailed analysis. I would also emphasize the importance of further population comparison, especially with other Maya populations or populations living in environmentally similar conditions. Such comparison helps to support the extent that the data are common to many socies as well as help identify unique health and growth conditions that are population-specific to Tipu.

The results of this study suggest that the juvenile population at Tipu did not experience much turmoil during their short lives, although they did die young. The patterns seen help to support the idea of a seemingly healthy juvenile population despite the arrival of the Spanish, which was undoubtedly related in large part to its location on the frontier. The unique history of Tipu suggests that this period in history in Mesoamerica is one characterized by much variation rather than the broad devastation often depicted.

APPENDIX A - Data

Table A1. *All Sample Sizes by Age*

Burial Number	Sex	Lower Age	Upper Age	Location	Anterior-Posterior	Medial-Lateral	Circumference	Linea Aspera	Medial	Lateral	Anterior
160	6	0	2	Inside, back	7.5mm 7.8mm	8.8mm 8.8mm	3cm 3cm	2.0mm 2.7mm	3.1mm 3.1mm	2.6mm 2.7mm	2.7mm 3.4mm
209	6	0.5	1	outside	7.8mm	9.6mm	3.2cm	1.2mm	1.3mm	1.6mm	1.0mm
287	6	0	2	outside	8.8mm 9.2mm	9.44mm 9.6mm	3.2cm 2.3mm	2.8mm 2.3mm	2.5mm 1.9mm	2.9mm 2.1mm	2.4mm 2.6mm
433	6	0.8	1	outside	9.9mm 8.7mm	9.6mm 10.1mm	3.2cm 3.3cm	3.0mm 2.7mm	2.7mm 2.3mm	1.3mm 1.6mm	2.4mm 2.8mm
449	6	0.5	1	outside	6.7mm	5.7mm	2.3cm	2.3mm	2.0mm	1.9mm	1.9mm
459	6	0	0	outside	6.7mm 6.5mm	5.2mm 1.8mm	2.3cm 2.2cm	2.5mm 2.4mm	1.7mm 1.7mm	1.6mm 1.6mm	1.6mm 1.7mm
20	6	1	3	outside	13.0mm 13.7mm	14.9mm 14.6mm	4.9cm 4.8cm	3.4mm 3.3mm	2.0mm 2.0mm	2.1mm 2.0mm	1.8mm 1.7mm
250	6	1	2	outside	10.1mm 10.2mm	9.1mm 9.0mm	3.3cm 3.3cm	2.4mm 1.9mm	1.8mm 1.8mm	1.7mm 1.8mm	2.0mm 1.8mm
346	6	1	3	Inside, back	11.7mm 11.8mm	10.3mm 10.1mm	3.8cm 3.7cm	1.7mm 1.9mm	1.6mm 1.6mm	1.8mm 1.8mm	1.8mm 1.9mm
435	6	1	2	outside	10.6mm 9.7mm	9.7mm 10.4mm	3.5cm 3.4cm	2.2mm 2.5cm	1.5mm 2.2mm	2.1mm 1.2mm	2.5mm 1.9mm
542	6	1	3	outside	11.6mm	9.5mm	3.6cm	1.6mm	1.4mm	1.3mm	1.6mm
117	6	2	4	Inside, back	10.4mm 9.9mm	11.1mm 10.9mm	3.7mm 3.6mm	3.0mm 2.8mm	2.4mm 1.6mm	2.5mm 1.9mm	1.9mm 1.4mm
149	6	2	10	Inside, back	18.6mm 19.2mm	18.2mm 11.9mm	6cm 6cm	4.8mm 4.5mm	4.0mm 5.0mm	3.8mm 3.6mm	5.2mm 3.9mm
170	6	2	4	outside	9.53mm 9.54mm	11.84mm 11.80mm	3.6cm 3.6cm	2.05mm 1.91mm	1.88mm 2.19mm	1.55mm 1.61mm	2.19mm 1.70mm
220	6	2	4	outside	9.71mm 9.96mm	12.51mm 12.07mm	3.4cm 3.8cm	3.15mm 2.35mm	3.55mm 2.80mm	2.56mm 2.90mm	2.83mm 2.71mm
266	6	2	4	Inside, back	10.34mm 12.14mm	12.05mm 11.4mm	3.8cm 3.8cm	2.79mm 2.41mm	2.39mm 2.26mm	1.69mm 1.63mm	2.18mm 2.23mm
431	6	2	4	outside	11.08mm 11.47mm	10.73mm 11.01mm	3.8cm 3.7cm	1.99mm 1.91mm	2.45mm 2.41mm	1.76mm 1.31mm	2.22mm 1.96mm

457	6	2	4	outside	12.41mm 12.77mm	11.0mm 11.3mm	3.9cm 3.9cm	2.24mm 2.59mm	2.66mm 1.84mm	1.69mm 2.44mm	1.99mm 2.25mm
458	6	2	4	outside	12.75mm	10.96mm	4cm	1.63mm	1.41mm	1.64mm	1.68mm
472	6	2	4	outside	11.34mm	9.43mm	3.6cm	2.01mm	1.42mm	2.14mm	1.72mm
485	6	2	4	outside	13.90mm	11.25mm	4.1cm	4.01mm	2.57mm	1.82mm	2.75mm
521	6	2	4	Inside, back	12.51mm 12.24mm	10.33mm 10.53mm	3.9cm 3.8cm	3.48mm 3.27mm	2.62mm 2.66mm	2.56mm 2.60mm	2.39mm 2.42mm
22	6	3	5	outside	13.0mm	13.2mm	13.6mm	1.8 mm	1.6mm	3.4mm	1.7mm
61	6	3	5	Inside, back	12.81mm 12.95mm	11.69mm 12.07mm	4.1cm 4.2cm	2.58mm 1.92mm	2.37mm 1.57mm	2.09mm 1.34mm	1.55mm 2.02mm
155	6	3	5	Inside, back	13.44mm	11.23mm	4.1cm	2.21mm	2.25mm	1.79mm	2.04mm
501	6	3	5	outside	12.64mm 12.54mm	12.05mm 11.85mm	4.0cm 4.0cm	2.64mm 2.76mm	1.91mm 2.39mm	1.69mm 1.82mm	1.98mm 2.13mm
225	6	3	5	outside	13.3mm 13.1mm	12.1mm 12.7mm	4.3cm 4.1cm	2.1mm 2.2mm	1.9mm 2.6mm	1.8mm 2.0mm	1.9mm 1.9mm
25	6	4	6	outside	13.1mm 13.1mm	11.3mm 11.9mm	4mm 4mm	3.0mm 2.8mm	2.5mm 2.1mm	2.2mm 2.2mm	2.3mm 2.9mm
162	6	4	6	outside	14.38mm	12.64mm	4.5cm	3.91mm	2.73mm	2.06mm	2.44mm
217	6	4	6	outside	15.21mm 15.23mm	13.66mm 13.60mm	4.8cm 4.8cm	4.15mm 3.48mm	3.26mm 2.45mm	2.46mm 2.68mm	2.48mm 2.76mm
41	6	5	7	Inside, back	14.45mm 14.41mm	12.987mm 12.61mm	4.5cm 4.5cm	2.97mm 3.19mm	2.31mm 2.50mm	2.00mm 2.35mm	2.56mm 2.32mm
181	6	5	7	Inside, front	17.30mm 16.71mm	15.37mm 15.13mm	5.2cm 5.2cm	4.54mm 5.04mm	3.06mm 3.18mm	3.27mm 2.09mm	3.46mm 3.10mm
242	6	5	7	outside	15.03mm	15.91mm	5.0cm	2.72mm	3.15mm	2.17mm	2.93mm
280	6	5	7		15.54mm 15.74mm	13.08mm 12.77mm	4.8cm 4.8cm	4.68mm 4.78mm	2.68mm 2.82mm	2.52mm 2.41mm	2.92mm 3.15mm
75	6	6	8	Inside, back	15.26mm	14.31mm	4.9cm	4.11mm	3.67mm	3.39mm	3.67mm
125	6	6	8	Inside, back	16.60mm	14.64mm	5cm	3.33mm	2.28mm	2.17mm	2.38mm
130	6	6	8	outside	15.55mm 16.93mm	16.43mm 15.17mm	5.2cm 5.3cm	4.61mm 4.52mm	4.21mm 3.90mm	3.45mm 2.72mm	5.02mm 3.63mm
351	6	6	8	outside	15.91mm 15.97mm	13.78mm 13.99mm	4.9cm 4.9cm	4.43mm 4.33mm	3.53mm 3.53mm	3.16mm 3.35mm	3.38mm 3.31mm
385	6	6	8	outside	15.66mm 14.85mm	13.49mm 13.50mm	4.9cm 4.9cm	4.12mm 4.09mm	3.83mm 3.84mm	3.77mm 3.80mm	3.47mm 3.43mm
387	6	7	9	Inside, back	18.20mm 18.53mm	15.72mm 15.27mm	5.5cm 5.6cm	3.40mm 4.14mm	2.93mm 2.79mm	1.88mm 2.48mm	3.38mm 3.36mm

392	6	7	9	Inside, back	16.78mm 16.21mm	15.68mm 15.52mm	5.5cm 5.3cm	4.09mm 3.93mm	3.26mm 3.22mm	2.29mm 2.42mm	2.69mm 2.99mm
397	6	7	9	Inside, front	17.48mm 17.44mm	16.41mm 17.11mm	5.5cm 5.9cm	3.83mm 3.55mm	2.93mm 2.98mm	2.61mm 2.17mm	2.99mm 3.22mm
398	6	8	10	outside	19.37mm	17.93mm	6.1cm	3.56mm	2.66mm	2.37mm	3.33mm
420	6	8	10	outside	16.28mm	15.75mm	5.2cm	4.12mm	3.15mm	2.51mm	3.43mm
426	6	8	10	outside	17.64mm 17.98mm	18.72mm 18.82mm	6cm 5.9cm	3.94mm 3.58mm	4.23mm 4.10mm	3.83mm 3.58mm	3.97mm 4.33mm
468	6	8	10	outside	16.83mm 16.98mm	17.07mm 17.05mm	5.5cm 5.5cm	4.37mm 4.84mm	3.94mm 3.19mm	2.83mm 2.67mm	3.38mm 3.81mm
98 B	6	9	11	outside	19.10mm	17.62mm	6cm	4.55mm	4.87mm	2.54mm	3.52mm
132 D	6	9	11	outside	19.11mm 19.44mm	17.69mm 18.03mm	6cm 6cm	4.97mm 5.24mm	4.48mm 4.72mm	3.76mm 3.63mm	5.07mm 4.25mm
6	6	9	11	Inside, back	18.83mm	15.55mm	5.6cm	3.43mm	3.44mm	3.10mm	3.66mm
40	6	9	11	outside	17.84mm 17.95mm	15.00mm 15.07mm	5.4cm 5.5cm	4.57mm 4.63mm	4.16mm 3.13mm	3.78mm 3.09mm	3.13mm 3.78mm
257	6	9	11	outside	18.15mm	18.96mm	5.9cm	4.33mm	4.69mm	2.98mm	4.47mm
416	6	9	11	outside	20.01mm	16.74mm	6.1cm	4.22mm	4.08mm	3.41mm	2.76mm
524	6	10	12	outside	19.82mm 19.83mm	17.04mm 17.24mm	5.9cm 5.9cm	4.11mm 4.02mm	3.97mm 3.85mm	2.92mm 2.73mm	3.65mm 3.78mm
548 B	6	10	12	outside	18.94mm 18.78mm	17.78mm 17.70mm	5.9cm 5.9cm	4.09mm 4.27mm	3.09mm 3.83mm	3.13mm 3.11mm	3.82mm 3.15mm
30	6	11	13	outside	21.77mm	18.69mm	6.4cm	4.33mm	4.34mm	3.73mm	3.93mm
127	6	11	13	outside	18.99mm 18.94mm	15.85mm 16.29mm	5.5cm 5.9cm	5.3mm 4.51mm	3.97mm 3.13mm	3.23mm 3.33mm	3.04mm 3.98mm
259	6	11	13	outside	21.99mm 22.15mm	18.51mm 18.34mm	6.8cm 6.5cm	6.32mm 6.62mm	3.83mm 3.83mm	3.34mm 3.11mm	4.46mm 4.81mm
359	6	11	13	outside	20.07mm	16.71mm	6cm	5.74mm	5.79mm	4.45mm	5.07mm
530	6	11	13	outside	19.75mm 20.28mm	16.16mm 16.13mm	5.9cm 5.9cm	5.52mm 5.18mm	3.51mm 3.31mm	2.85mm 3.44mm	3.46mm 3.78mm
401	6	12	14	Inside, front	20.41mm 20.36mm	20.94mm 21.31mm	7.6cm 6.7cm	6.71mm 6.72mm	6.73mm 6.87mm	4.96mm 5.15mm	6.94mm 7.21mm
413	6	12	14	outside	21.51mm	17.61mm	6.2cm	6.95mm	4.61mm	3.51mm	4.57mm
480	6	12	15	outside	23.10mm	21.98mm	7.2cm	6.43mm	5.91mm	3.60mm	6.49mm
396	6	12	14	outside	22.35mm 22.18mm	17.23mm 17.11mm	6.5cm 6.5cm	6.27mm 6.18mm	3.60mm 4.71mm	4.01mm 4.03mm	4.41mm 3.90mm
296 A	2	16	21	Inside, front	22.04mm 22.19mm	22.45mm 22.64mm	7.1cm 7.1cm	6.35mm 6.50mm	6.26mm 6.83mm	4.29mm 4.10mm	6.70mm 6.15mm

63	2	16	20	outside	21.05mm	23.80mm	7.2cm	5.76mm	8.87mm	4.77mm	9.15mm
157	2	17	25	Inside, front	21.41mm	25.69mm	7.5cm	6.78mm	7.84mm	5.04mm	7.84mm
176	5	17	25	outside	27.33mm	21.84mm	7.8cm	9.55mm	5.52mm	6.77mm	7.19mm

REFERENCES

Agarwal, S. C. (2016). Bone morphologies and histories: Life course approaches in bioarchaeology. *American Journal of Physical Anthropology*, *159*, 130-149.

Ardren, T. (2002). Women and gender in the ancient Maya world. In *Ancient Maya Women.* T. Arden (ed.), 1-11. Walnut Creek: Altamira.

Bass, W.M., D.R. Evans, & R. L. Jantz (1971) *The Leavenworth Site Cemetery: Archaeology and Physical Anthropology*. University of Kansas Publications in Anthropology, 2. Lawrence: University of Kansas Press.

Bianchi, S. A. (2020). Nutrition at Tipu: A Comparative Analysis of Juvenile Health in Maya Populations. Master's Thesis. University of Southern Mississippi.

Bleuze, M. (2007). Health status and long bone lengths among Maya sub-adults from two coastal sites in Belize. *Totem: The University of Western Ontario Journal of Anthropology*, *15*, 66-79.

Bogin, B. (1999). Evolutionary perspective on human growth. *Annual Review of Anthropology*, *28*(1), 109-153.

Cameron, N. (2012). The human growth curve, canalization and catch-up growth. In *Human Growth and Development*. N. Cameron & L. Schell (eds.), 1-22. New York: Academic Press.

Cohen, M. N., O'Connor, K., Danforth, M., Jacobi, K., & Armstrong, C. W. (1994). Health and death at Tipu. In *In the Wake of Contact: Biological Responses to Conquest.* C. S. Larsen & G. J. Milner (eds.), 121-133. New York: Wiley-Liss.

Danforth, M. E., Jacobi, K. P., & Cohen, M. N. (1997). Gender and health among the colonial Maya of Tipu, Belize. *Ancient Mesoamerica*, *8*(1), 13-22.

Danforth, M. E., Wrobel, G. D., Armstrong, C. W., & Swanson, D. (2009). Juvenile age estimation using diaphyseal long bone lengths among ancient Maya populations. *Latin American Antiquity*, *20*(1), 3-13.

Doube, M., Kłosowski, M. M., Arganda-Carreras, I., Cordelières, F. P., Dougherty, R. P., Jackson, J. S. & Shefelbine, S. J. (2010). BoneJ: Free and extensible bone image analysis in ImageJ. *Bone*, *47*(6), 1076-1079.

Garn, S., Guzmán, M. A., and Wagner, B. (1969) Subperiosteal gain and endosteal loss in protein-calorie malnutrition. *American Journal of Physical Anthropology, 30,* 153-155.

Graham, E. (2011) *Maya Christians and Their Churches in Sixteenth-Century Belize*. Tallahassee: University Press of Florida.

Graham, E., Pendergast, D. M., & Jones, G. D. (1989). On the fringes of conquest: Maya-Spanish contact in colonial Belize. *Science*, *246*(4935), 1254-1259

Gomberg, Emmalea. (2018). Investigating Possible Scurvy in the Contact Maya of Tipu. Master's Thesis. University of Southern Mississippi.

Harvey, A. R. (2011). Consequences of Contact: An Evaluation of Childhood Health Patterns Using Enamel Hypoplasias Among the Colonial Maya of Tipu. Master's Thesis. University of Southern Mississippi.

Herndon, K. S. (1994). The Children of Tipu: Gender, Health, and Social Change in a 16th Century Maya S. Master's Thesis. University of Southern Mississippi.

Hiers, Chaney (2014) Assessment of Age at Weaning for Post-Contact Maya of Tipu, Belize, Using Stable Carbon, Nitrogen, and Oxygen Isotope Ratios. Master's Thesis. Louisiana State University.

Hinkes, M. J. (1983) Skeletal Evidence of Stress in Subadults: Trying to Come of Age at Grasshopper Pueblo. Ph.D. Dissertation. University of Arizona.

Hummert, J. R. (1983). Skeletal growth and dietary stress among subadults from Nubia's Batn el Hajar. *American Journal of Physical Anthropology, 62*, 167-76

Huss-Ashmore, R., Goodman, A. H., & Armelagos, G. J. (1982). Nutritional inference from paleopathology. *Advances in Archaeological Method and Theory, 5*, 395-474.

Jacobi, K. P. (2000). *Last Rites for the Tipu Maya: Genetic Structuring in a Colonial Cemetery*. Tuscaloosa: University of Alabama Press.

Jones, G. D. (1989). *Maya Resistance to Spanish Rule: Time and History on a Colonial Frontier.* Albuquerque: University of New Mexico Press.

Jones, G., Riley, M., & Dwyer, T. (2000). Breastfeeding in early life and bone mass in prepubertal children: a longitudinal study. *Osteoporosis International*, *11*(2), 146-152.

Keith, M. S. (1981). Cortical bone loss in juveniles of Dickson Mounds. *Biocultural Adaptation: Comprehensive Approaches to Skeletal Analysis*. D. L. Martin and M. P. Bumsted (eds.), 67-79. Amherst: University of Massachusetts Press.

López de Cogolludo, D. (1971) *Los Tres Siglos de la Dominación Española en Yucatan: Osea Historia de Esta Provincia*, vols. 1 & 2. Verlagsanstalt Graz: Akademische Druck.

Manifold, B. M. (2014). Bone mineral density in children from anthropological and clinical sciences: a review. *Anthropological Review, 77*(2), 111-135

Mays, S., Ives, R., & Brickley, M. (2009). The effects of socioeconomic status on endochondral and appositional bone growth, and acquisition of cortical bone in children from 19th century Birmingham. England. *American Journal of Physical Anthropology*, *140*, 410–416

Noldner, L. K., & Edgar, H. J. H. (2013). Technical note: Representation and analysis of enthesis morphology. *American Journal of Physical Anthropology, 152*(3), 417-424.

Peate, I., & Gormley-Fleming, E. (eds.). (2015). *Fundamentals of Children's Anatomy and Physiology*. New York: John Wiley & Sons.

Pendergast, D. M. (1981). Lamanai, Belize: Summary of excavation results, 1974–1980. *Journal of Field Archaeology, 8,* 29–53.

Pendergast, D. M. (1993). Worlds in collision: The Maya/Spanish encounter in sixteenth and seventeenth-century Belize. *Proceedings of the British Academy, 81*, 105-143.

,

Pfeiffer, S. (2006). Cortical bone histology in juveniles. *Documenta Archaeobiologiae*, *4*, 15-28.

Storey, R. (1992). The children of Copan. Ancient Mesoamerica 3: 161–167

Simmons, S. E. (2002). Late Postclassic-Spanish colonial period stone tool technology in the southern Maya lowland area: The view from Lamanai and Tipu, Belize. *Lithic Technology, 27*(1), 47-72

Ubelaker, D. H. (1974). *Reconstruction of Demographic Profiles from Ossuary Skeletal Samples: A Case Study from the Tidewater Potomac*. Smithsonian Contributions to Anthropology No.18. Washington: Smithsonian Institution Press

White, C. D., Wright, L. E., & Pendergast, D. M. (1994). Biological disruption in the early colonial period at Lamanai. In *In the Wake of Contact: Biological Responses to Conquest.* C. S. Larsen & G. R. Milner (eds.), 135-154. New York: Wiley-Liss.

Wood, J. W., Milner, G. R., Harpending, H. C, & Weiss, K. M. (1992). The osteological paradox: problems of inferring prehistoric health from skeletal samples [and comments and reply]. *Current Anthropology*, *33*(4), 343-370.

Wright, L. E., & Chew, F. (1998). Porotic hyperostosis and paleoepidemiology: A forensic perspective on anemia among the ancient Maya. *American Anthropologist*, *100*(4), 924-939.

Wright, L. E., & Vásquez, M. A. (2003). Estimating the length of incomplete long bones: forensic standards from Guatemala. *American Journal of Physical Anthropology*, *120*(3), 233-251.

Wrobel, G. D., Danforth, M. E., & Armstrong, C. (2002). Estimating sex of Maya skeletons by discriminant function analysis of long-bone measurements from the protohistoric Maya site of Tipu, Belize. *Ancient Mesoamerica*, *13*(2), 255-263.